WHOI-2005-10

Woods Hole Oceanographic Institution

The Determination of the Elastic Modulus of Rubber Mooring Tethers and their use in Coastal Moorings

by

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December 2005

Technical Report

Funding was provided by the Gulf of Maine Ocean Observing System (GoMOOS under ONR grant N0014-01-1-0999), NOAA-UNH CINEMAR (NOAA Grant Number NA16RP1718), and GLOBEC (NSF OCE93-13670 and OCE02-27679).

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Approved for Distribution:

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The Determination of the Elastic Modulus of Rubber Mooring Tethers and Their Use in Coastal Moorings

James D. Irish, Walter Paul and Dave Wyman

1. ABSTRACT

Compliance must be supplied to any surface mooring to allow the buoy to move with the waves and currents, and remain moored in position. This can be supplied with a traditional chain catenary or newer compliant elastic tether or stretch hose technologies. Some applications of each of these three techniques are shown, with the emphasis placed on the use of compliant elastic tethers. For modeling and designing these moorings, the elastic modulus of the tether material must be known. Therefore, a new and used piece of elastic material was terminated, tested for the stretch-strain relationship under set conditions, and the elastic modulus calculated. For these tests, the elastic tether was stretched out to a mean elongation between 100 and 250%, then cycled about that stretch by ±25 and ±50% to duplicate a moored application. The resultant elastic modulus is presented to aid in mooring design. At low elongations, the elastic modulus is constant at about 125 PSI, but as the mean elongation increases the modulus increases, and as the cycle tension increase the modulus also increases, reaching a maximum of 900 PSI at 275% stretch.

2. Introduction/Background:

2.1. Coastal Moorings: Coastal moorings require some kind of compliance to allow the buoy and mooring to move with tidal height changes, tidal and low frequency currents, and surface waves. In continental shelf and coastal deployments, chain catenary moorings have often provided this compliance. This configuration (Figure 1) consists of light chain or wire rope in the water column down to near the bottom, then heavier chain running along the bottom to the anchor.

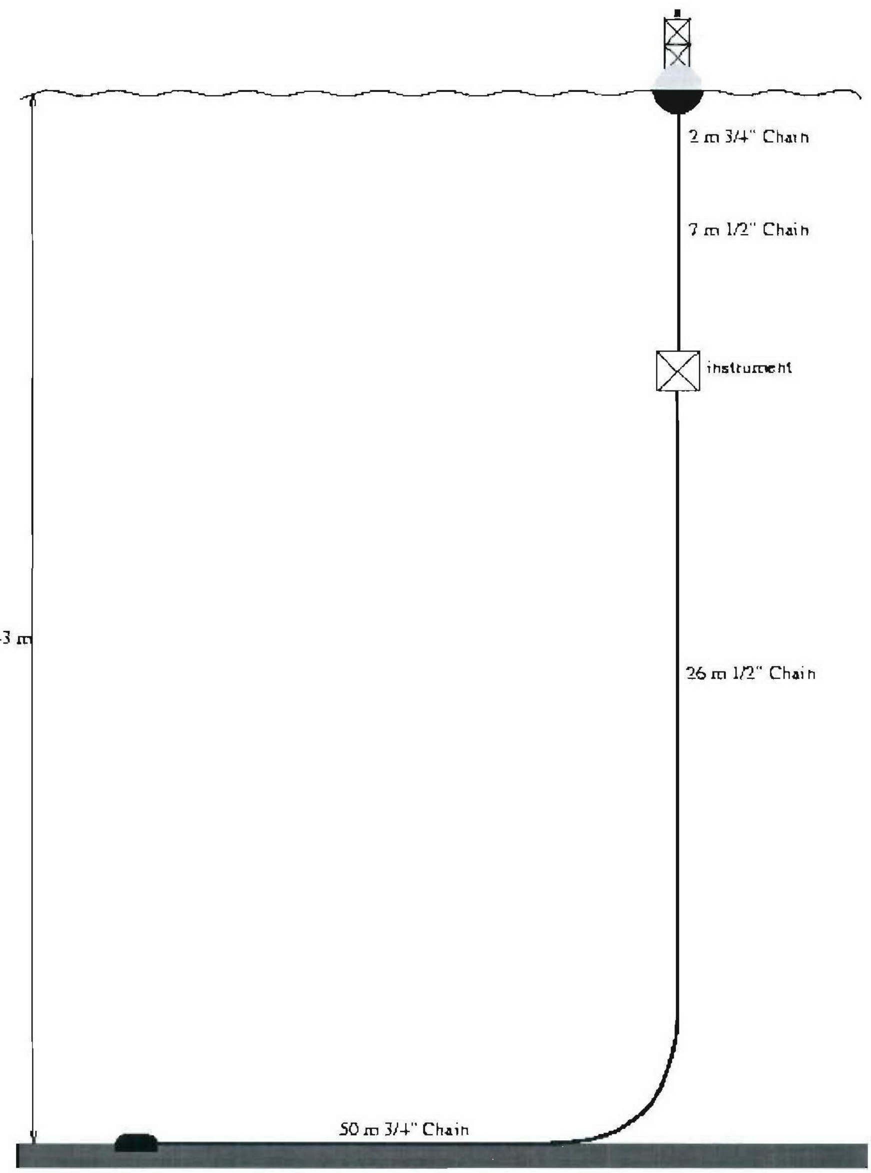

Figure 1. A Standard Chain Catenary Mooring Configuration. This mooring had nearly a scope of 2, and was designed and modeled for a mooring on the crest of Georges Bank.

The compliance to allow the buoy to move with the currents and waves is provided by the heavier chain on the bottom being lifted up and down by the buoy. However, this configuration has the problem of wrapping up the chain in a knot if swivels are not provided at both ends of the chain (experienced with 3-m discus buoys moored on the Northeast Peak of Georges Bank in the Global Ocean Ecosystem Dynamics Georges Bank Program - GLOBEC in 1998-99). Also, if the currents are strong enough to take all the compliance out of the mooring (see Figure 14 below), the buoy is restricted from moving with the waves and results in buoy/sensor damage by the waves breaking over the buoy. In the deep ocean, compliance has been supplied by long lengths of Nylon rope. However, in shelf regions, there is not enough depth to obtain the required compliance with rope.

Two alternatives have been successfully used for these coastal and shelf applications – compliant elastic tethers and stretch hoses. Either of these two components can provide the additional compliance per unit length required for coastal moorings. Each of these techniques has advantages and disadvantages.

2.2. Stretch Hoses: The stretch hoses (Figures 2, 3 and 4) are made of rubber and tire cord hand laid up over a mandrel, and are restricted in length to 100 feet maximum per hose. However, several hoses can be used in a mooring (perhaps between sensor packages as shown in Figure 2) to obtain the required compliance. The hoses are reinforced with counter-helical layers of nylon tire cord as part of the hose structure. Through selection of the counter-helical wrap angle the ultimate hose stretch can be varied between 30 and 140 percent. This construction allows the rubber, which stretches easily, to take most of the load at low stretch, but when the hose begins to stretch more than the designed working length, the tension is shared between the rubber and cords. The tire cords take the dominant part of the load as stretching continues.

Stretch hoses are stiffer and significantly stronger than the compliant elastic tethers due to the inclusion of the nylon tire cord layers. The hoses are terminated with standard pipe flanges, which are sometimes more difficult to configure into the mooring. Another advantage of the hose configuration is that electrical conductors can be embedded into the hose wall (Figure 4) during construction so that electrical power and signals can be sent past the compliant mooring element. The specially constructed conductors are spiraled around the mandrel with a larger wrap angle than the nylon tire cord so that there is near zero stretch of the electrical conductors, with the stretching limited to the extension of the spiraled configuration in the hose. This configuration has worked well in mooring a feed buoy off New Hampshire in an aquaculture demonstration program (Fullerton et al., 2004). Power is sent down to video cameras inside a submerged aquaculture net cage, and signals sent to the feed buoy for relay to shore. Also water conditions are measured with a Sea Bird Electronics SeaCat in the fish cage and the information telemetered to the buoy and relayed to shore. Electrical conductors have also been put inside the hose (Figure 2) as rubber coil cords – a larger version of the telephone headset cord. This is only practical for hose configurations with lower stretch.

2.3. Elastic Tethers: Compliant elastic tethers are not as stiff as rubber hoses and can stretch to several hundred percent without breaking. Some advantages of rubber tethers are:

1. They provide a taut mooring so that all mooring components are off the bottom so that lighter weight components can be used since wear against the bottom doesn't have to be considered.

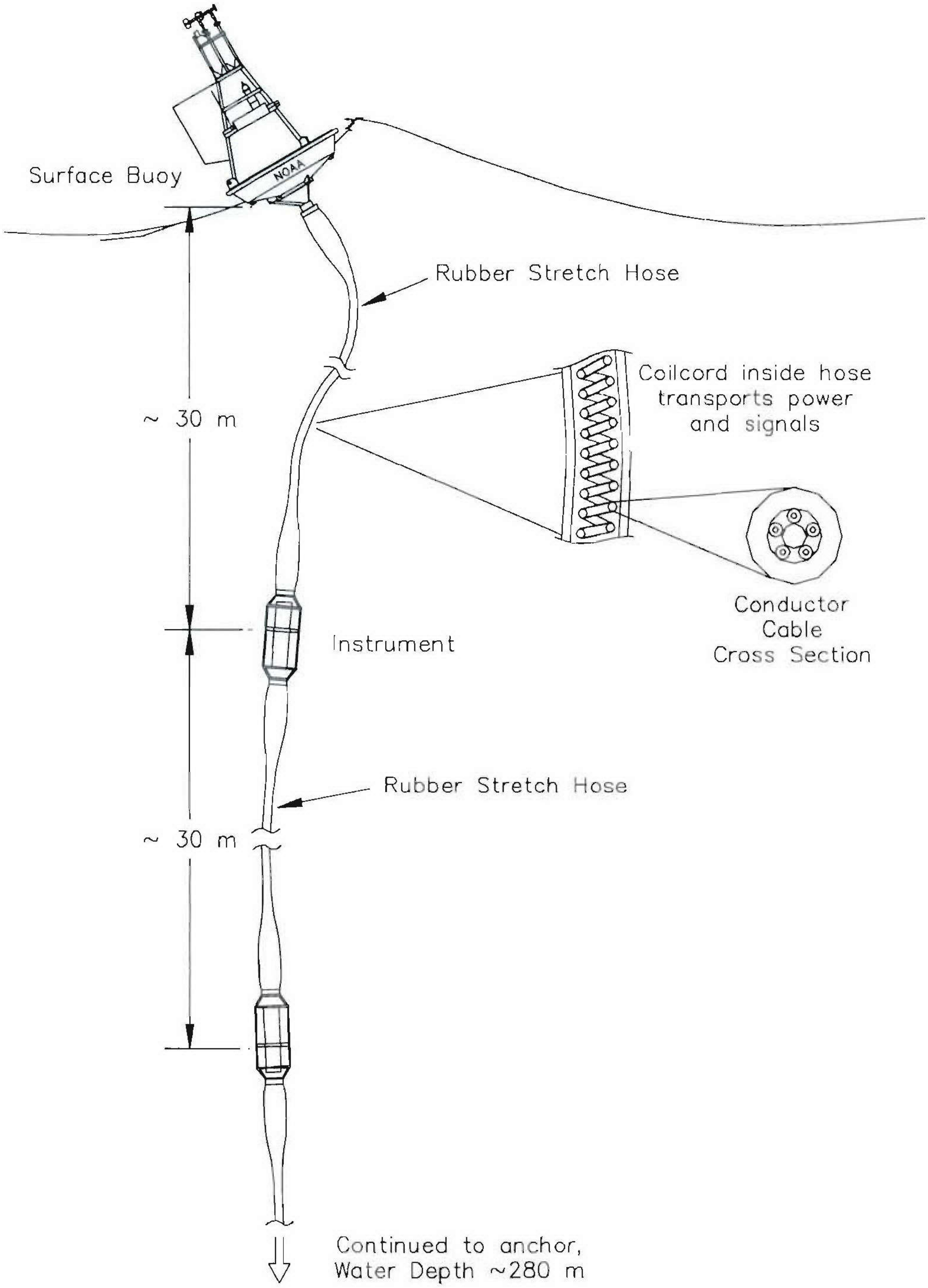

Figure 2. Stretch hose mooring with hoses linking instrument packages. In this configuration the electrical conductors are inside the stretch hose in the form of a coil cord (like a telephone headset cable).

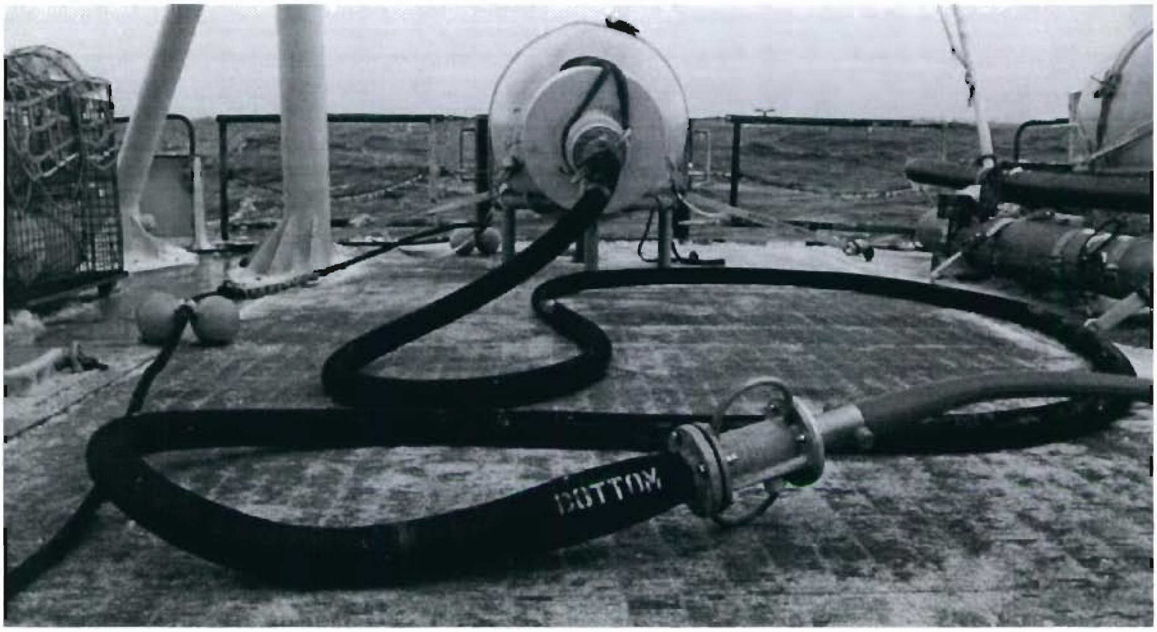

Figure 3. Stretch hose attached to the bottom of a telemetry buoy.

Figure 4. Constructing compliant stretch hose around a mandrel. After the initial rubber and cords are assembled, the electrical conductors shown being helically wound around the hose before the final layer of rubber is applied and the whole hose cured.

2. The positive tension on the bottom of the buoy provides a stiffer riding buoy that does not rock back and forth with the waves as much as a chain catenary mooring, and can accommodate servicing personnel without dangerously tipping (Figure 5). Since the buoy does not rock as much as with a chain catenary mooring, it provides a better platform from which to make meteorological and oceanographic observations.
3. The tethers stretch with the waves to reduce "shock" loading. Without the higher tensions found in a chain catenary mooring, an elastic tether mooring allows lighter weight mooring components to be used. This means that the buoy can be smaller in size as it doesn't have to have the additional floatation to carry the additional mooring weight. Also, the mooring components and anchor can be smaller, lighter weight and therefore the whole mooring is lower in cost. This lighter weight approach makes in easier, and safer to launch and recover.

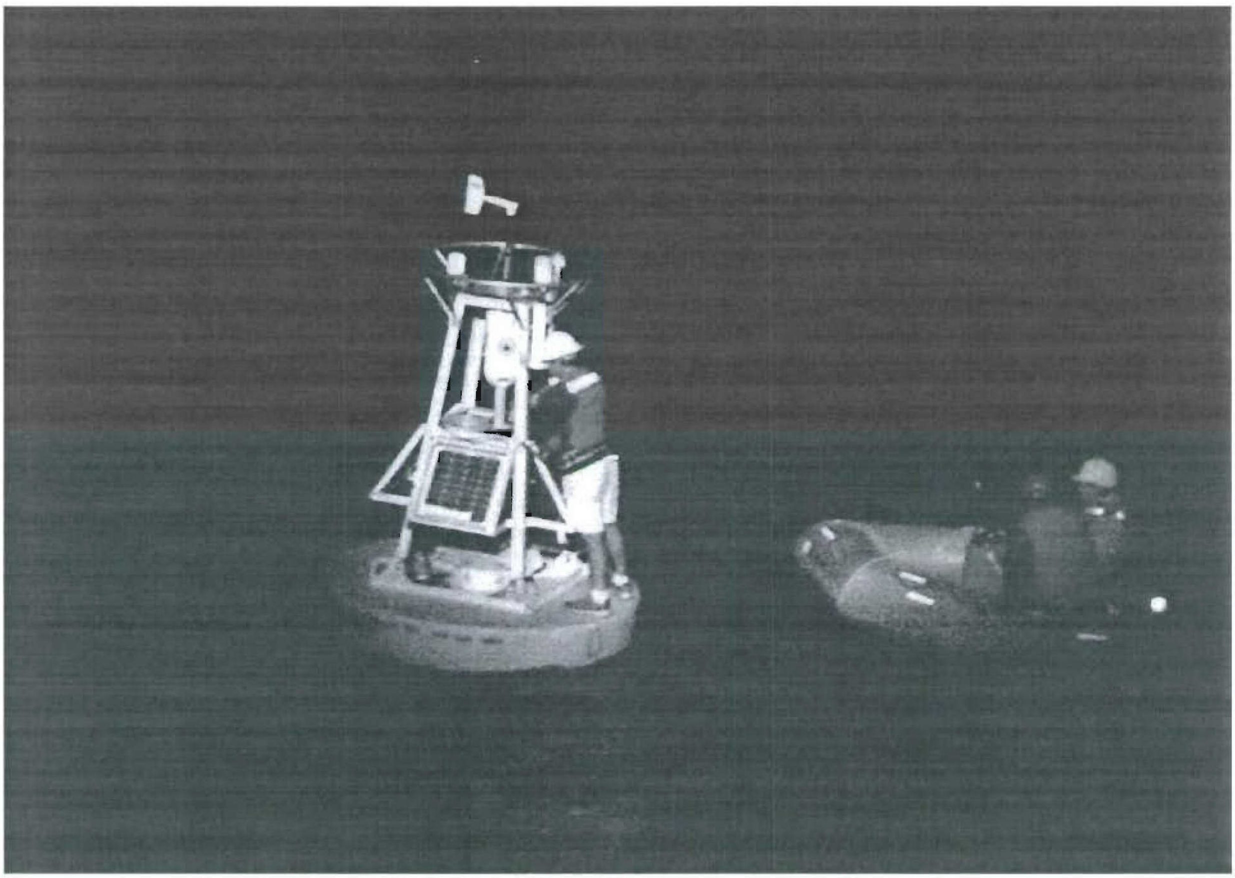

Figure 5. Scott Worrilow on a buoy on Georges Bank in July 1999 in calm seas repairing the guard light. The buoy is stable because of the elastic tether's downward force of about 500 lbs.

Some disadvantages of the elastic tether mooring are:

1. An acoustic release must be used, as the mooring cannot be recovered by pulling up the mooring from the surface This increases the cost of the mooring. An alternative in shallow water is diver retrieval by attaching a line on the mooring below the tethers. This puts personnel at higher risk, but works well.
2. The elastic tethers are more subject to breaking than a chain catenary mooring. During 5 years of mooring deployments on Georges Bank in GLOBEC (Irish, 2000) about 1.5

times the number of elastic tether science moorings were cut free than nearby chain catenary guard moorings. The majority of these failures were attributed to fishing activity in the region. If fishermen tangle with a mooring, the probability is that the mooring will be cut free before the fishing gear is lost. Tangling with fishing activities can also stretch the tethers beyond their working elongation to the point where the splices slip and need replacing, but the elastic tether material is generally still usable.

2.3.1. Terminating: The compliant elastic elements discussed and tested here are made from nominal 1" diameter Natsyn rubber, terminated by Buoy Technology Inc. of Concord, NH (Wyman, 1982). The actual diameter of the commercially supplied material has varied from 0.9 to 1.1". A critical factor in tether survival is to minimize stress concentration and failure at the termination. The tether is terminated by wrapping it around a thimble and laying it back on itself and securing the tether with self vulcanizing tape. There is the potential for stress concentration at the point where the single tether turns into two at the toe of the splice so the splice must be made to stretch as much like the rest of the elastic tether as possible, but without slipping. The slipping of a splice is an indication of either a bad splice, or, more typically, a tether that has been severely pulled so that the splice slipped. A curved splice (see Figure 7) is the result of one side of the slice slipping. The slight curving in the toe of the splices seen in Figure 6 (lower left hand side) is more typical of the curving in an old splice and often a new splice in the construction process and not a splice slip. Typically splices that show less than 45° bending are reused. One bent at nearly 90° was successfully reused. When a pulled splice is recovered, it is generally straight, but soon relaxes into the typical curved shape.

2.3.2. Tether Assembly: A tether assembly is made from several elastic elements shackled to a circular bridle to distribute the tension among the tethers (Figures 6 and 7). The length of the tether assembly is determined by the amount of elongation required to give the mooring the necessary compliance to move with the currents and waves. The number of tethers is selected for the desired working tension in the mooring. As a single tether breaks at something like 800 lbf, the number of tethers also gives an indication of the maximum tension allowed before failure of the tether assembly. The New Hampshire environmental mooring (Figure 10) has four tethers in an assembly (Figure 6) and a deployed tension with no waves or currents of around 350 lbf. With 1 kt currents (typical maximum in the region) and 7 m waves, the tensions rise to about 800 lbf. In GLOBEC with 6 tethers (Figure 7), the deployed tension with no waves or currents is about 500 lbf.

2.3.3. Configurations: The elastic tethers can be located anywhere along the mooring. Figure 7 shows the elastic tethers in the middle of the mooring with sensor packages above it and the release and bottom flotation below (Irish and Kery, 1996, Irish, 1997, Paul, et al., 1999). Figure 8 shows the elastics at the bottom of the mooring (Wood and Irish, 1987, Geyer et al., 1992, Irish et al., 1992, Irish and Kery, 1996, Irish, 1997 and 2000). The location at the bottom was selected because sensors spaced along the mooring cable received power down the cable and sent signals back up the cable to the buoy for storage and telemetry. As the tethers normally don't have the capability of supporting electrical conductors, they must be located below the electromechanical cable. In bottom located tether applications, both four (Wood and Irish, 1987) and six tethers have been successfully used in an assembly (Irish and Kery, 1996, Irish 1997 and 2000). Figure 6 shows the four-tether assembly used in the mooring configuration in Figure 10, and Figure 7 shows a six-tether assembly after recovery used in the mooring configuration shown in Figure 9.

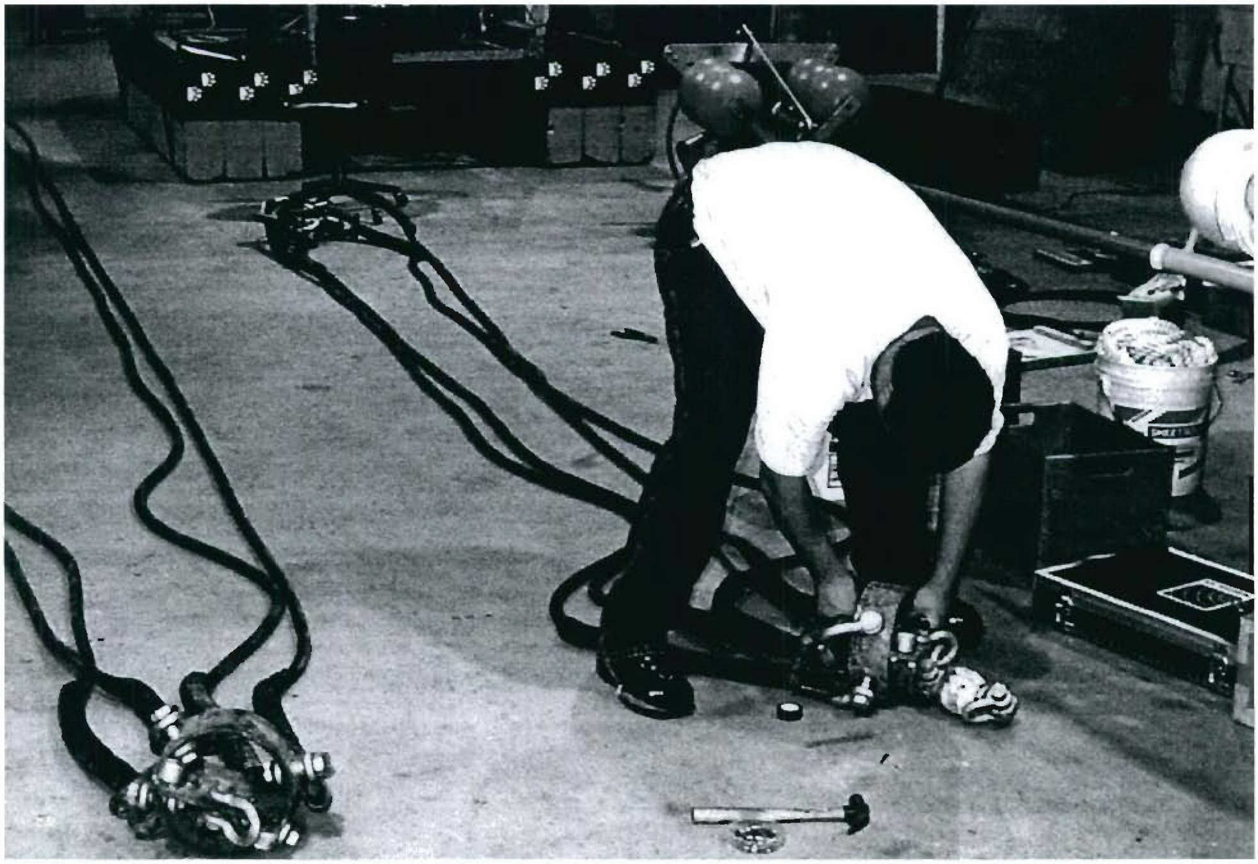

Figure 6. Compliant Tether Assembly. Four elastic tethers are attached to bridle assemblies at each end. A swivel prevents the tether assembly from becoming twisted (seen on the bridle assembly on the right). These two tether assemblies are used on the environmental monitoring mooring deployed off New Hampshire (see Figure 9).

Elastic tethers have been used at the top of a mooring (Figure 11) to decouple buoy motion with the surface wave field from deep current meters (Geyer et al., 1992). The Vector Averaging Current Meter (VACM) utilizes a Savonius rotor to measure current speed and a vane to obtain direction. If the VACM were moved up and down by the waves on a mooring that is tilted, the non-linearly of the Savonius rotor can rectify the oscillating motion due to the waves and thus contaminate the current meter observations. On a taut mooring with the compliance at the top, the vertical motion of the VACM below the tether was greatly reduced, and the contamination of the observations minimized.

More recently the elastic tethers have been placed at the top of the mooring (Figure 10) to allow the buoy to move freely with the surface wave field and measure waves (Irish et al., 2001, Irish and Fredriksson, 2003a and 2003, Irish et al., 2004). In the surface wave measuring applications we have used one tether (Irish et al., 2001) and four tethers (Irish and Fredriksson, 2003a and 2003b). The number of tethers was increased to four, when degradation of the wave data was observed because the buoy was "tilting" with the wave field. With only one tether, the restoring force was about 60 to 80 lbf. at slack currents. With four tethers, the tension was 400 to 800 lbf. depending on the currents, and this additional tension made the mooring stiffer, and the buoy ride up and down with the waves with reduced rocking, and produced less "noisy" data because the buoy rode more vertically (Irish and Fredriksson, 2003a).

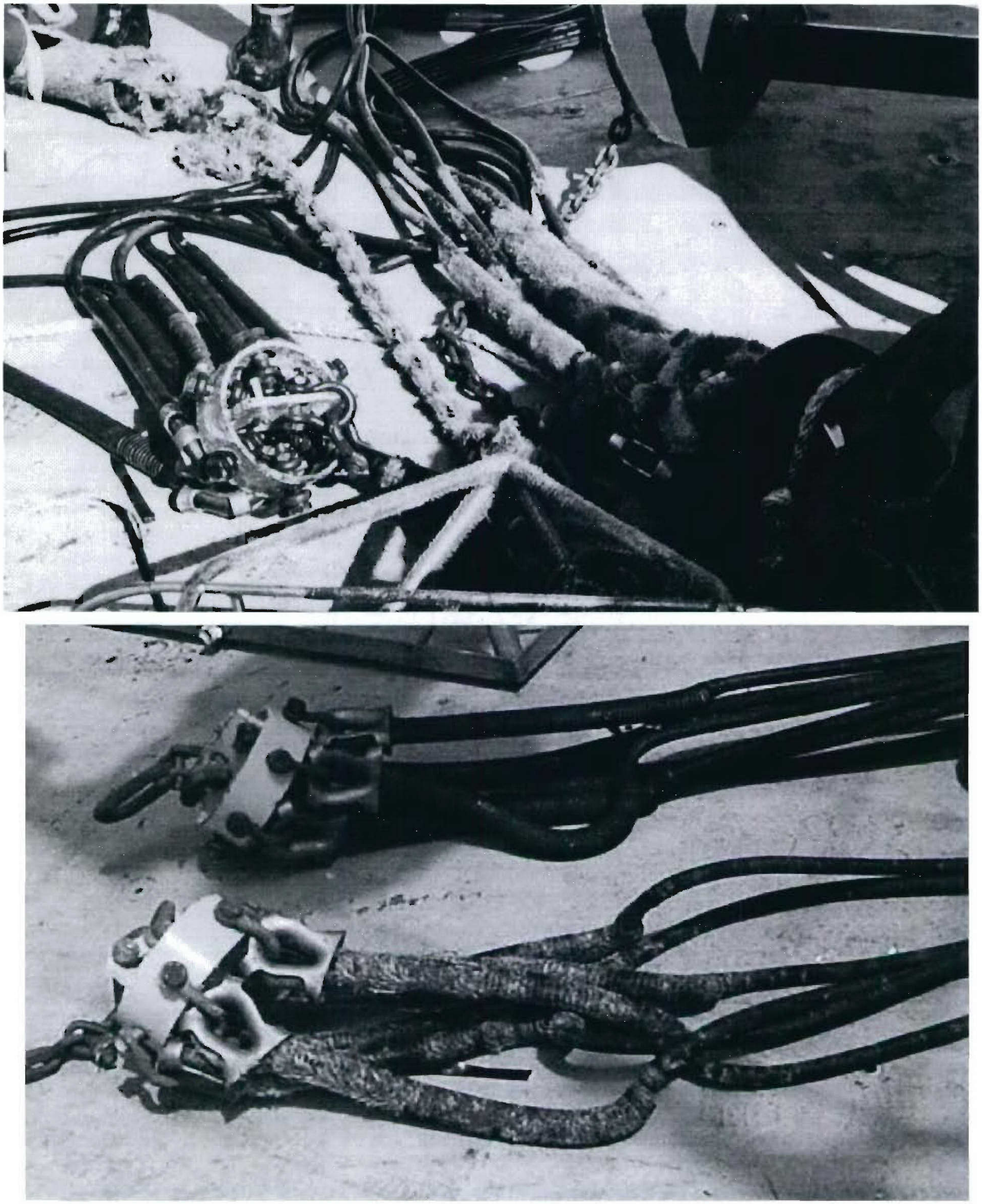

Figure 7. Two six-element elastic tether assemblies after six months deployment on Georges Bank in GLOBEC. The top is from the Northeast Peak and the bottom from the Southern Flank. The mooring configuration for both tethers is shown in Figure 9. The splices in the top picture show no curving due to over tensions, but the bottom ones show a little slippage, but the tethers were successfully redeployed. Only a little biofouling is observed on each assembly.

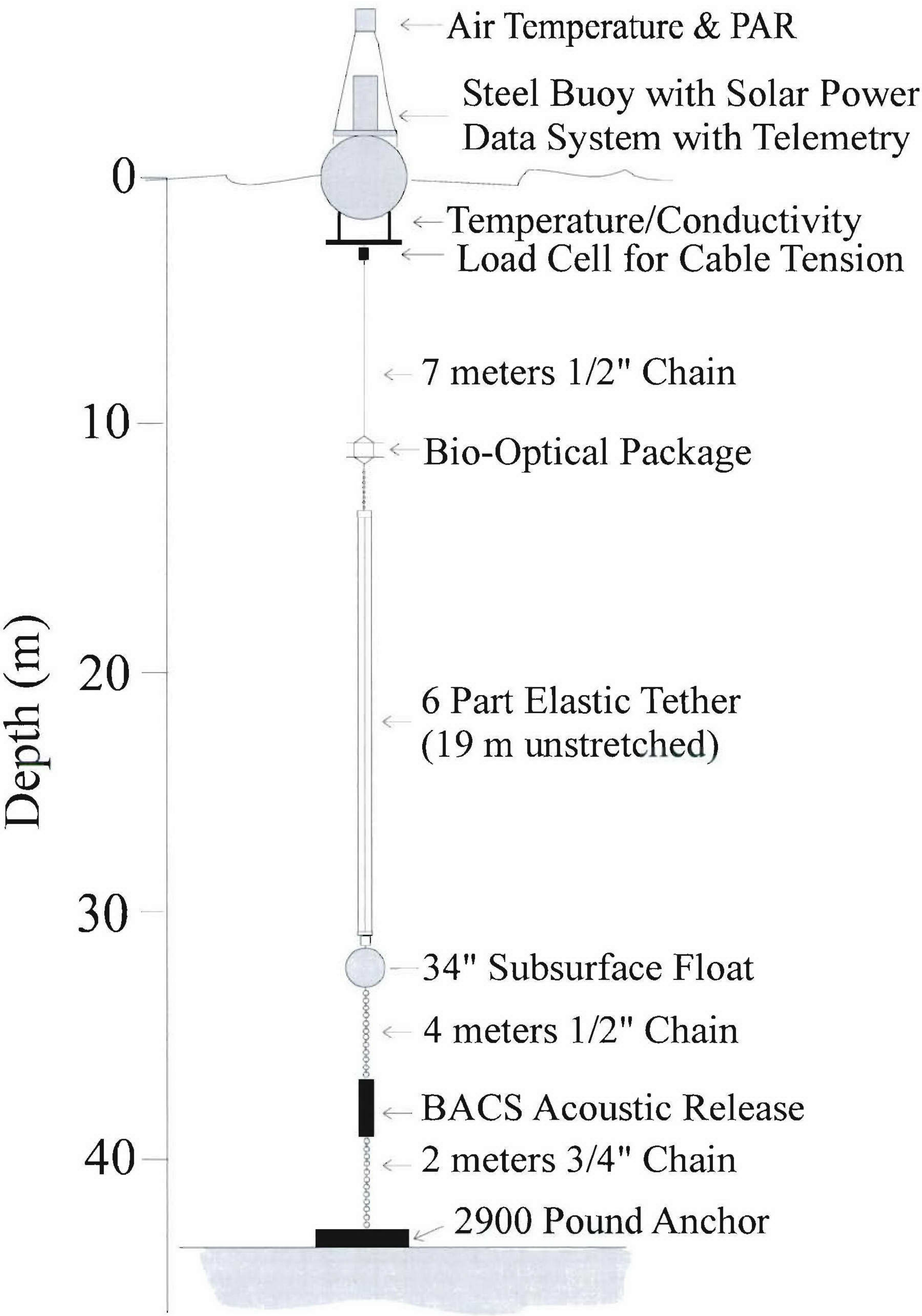

Figure 8. Compliant Elastic Tether used in the middle of the mooring deployed on the Crest of Georges Bank during GLOBEC.

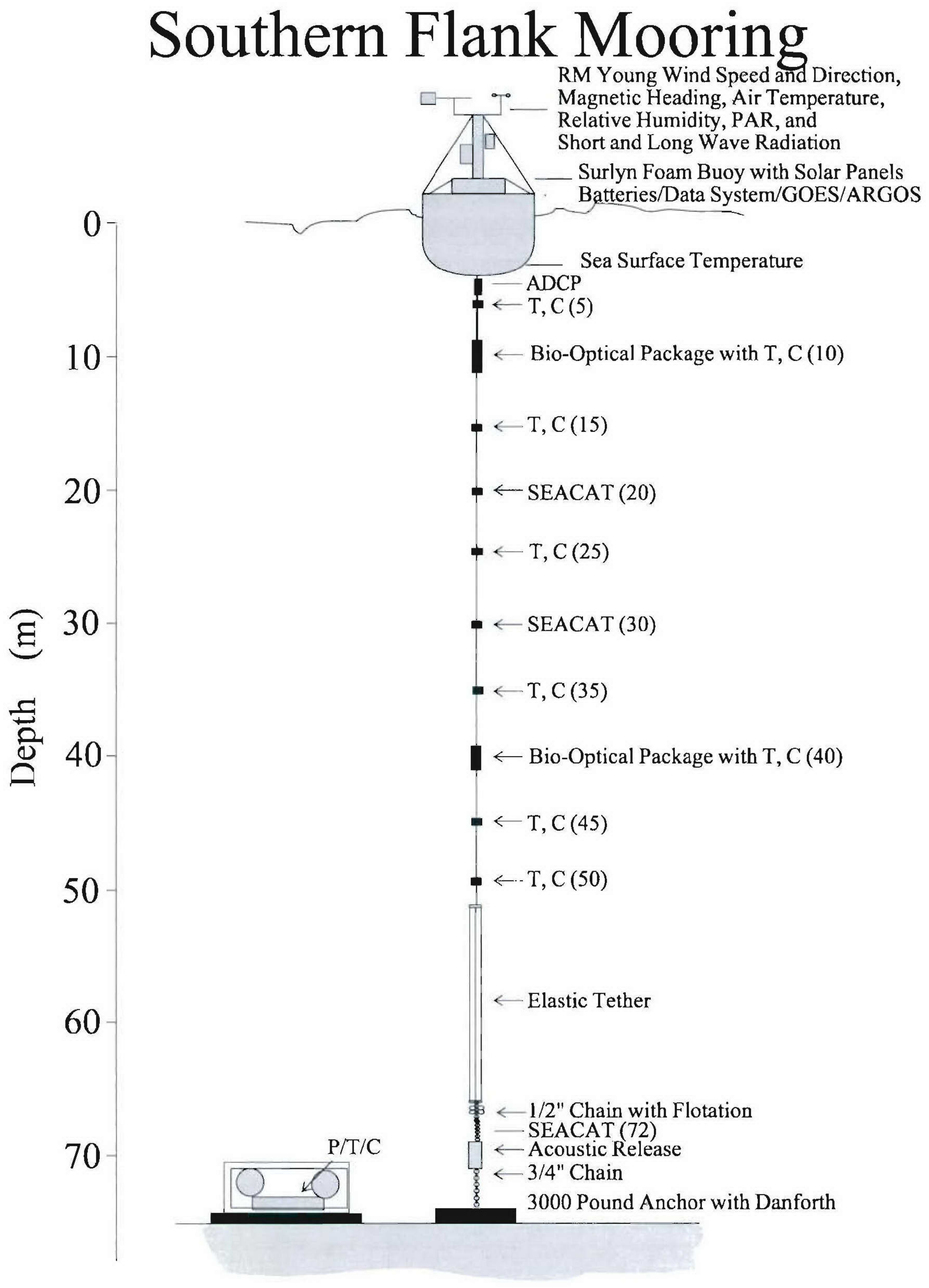

Figure 9. GLOBEC Southern Flank Mooring uses the compliant tether at the bottom so that the electromechanical mooring cable can send signals from the sensors to the buoy for logging and telemetry.

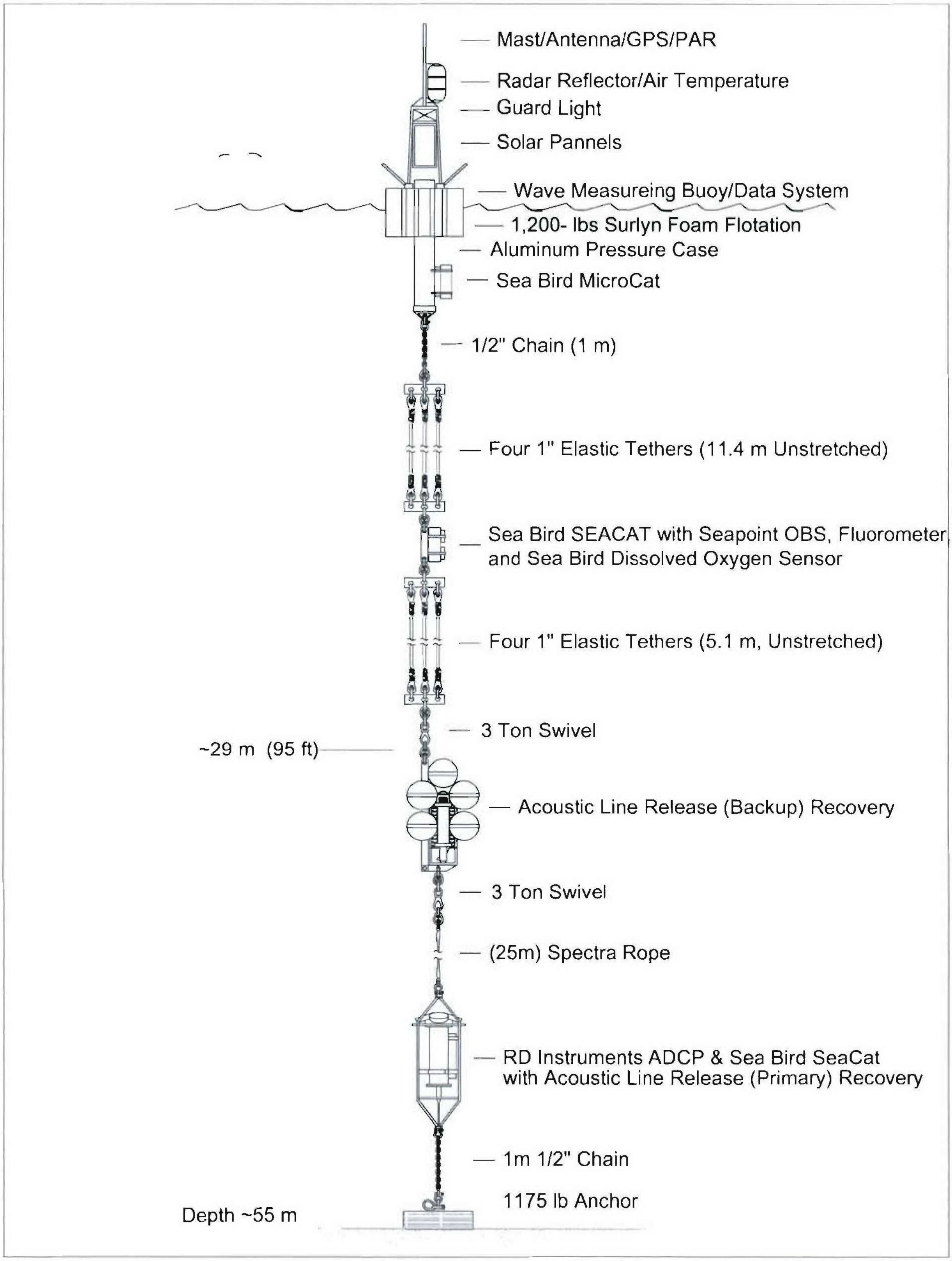

Figure 10. Compliant elastic tethers used in top of environmental monitoring mooring deployed off New Hampshire to allow the buoy to follow the surface waves.

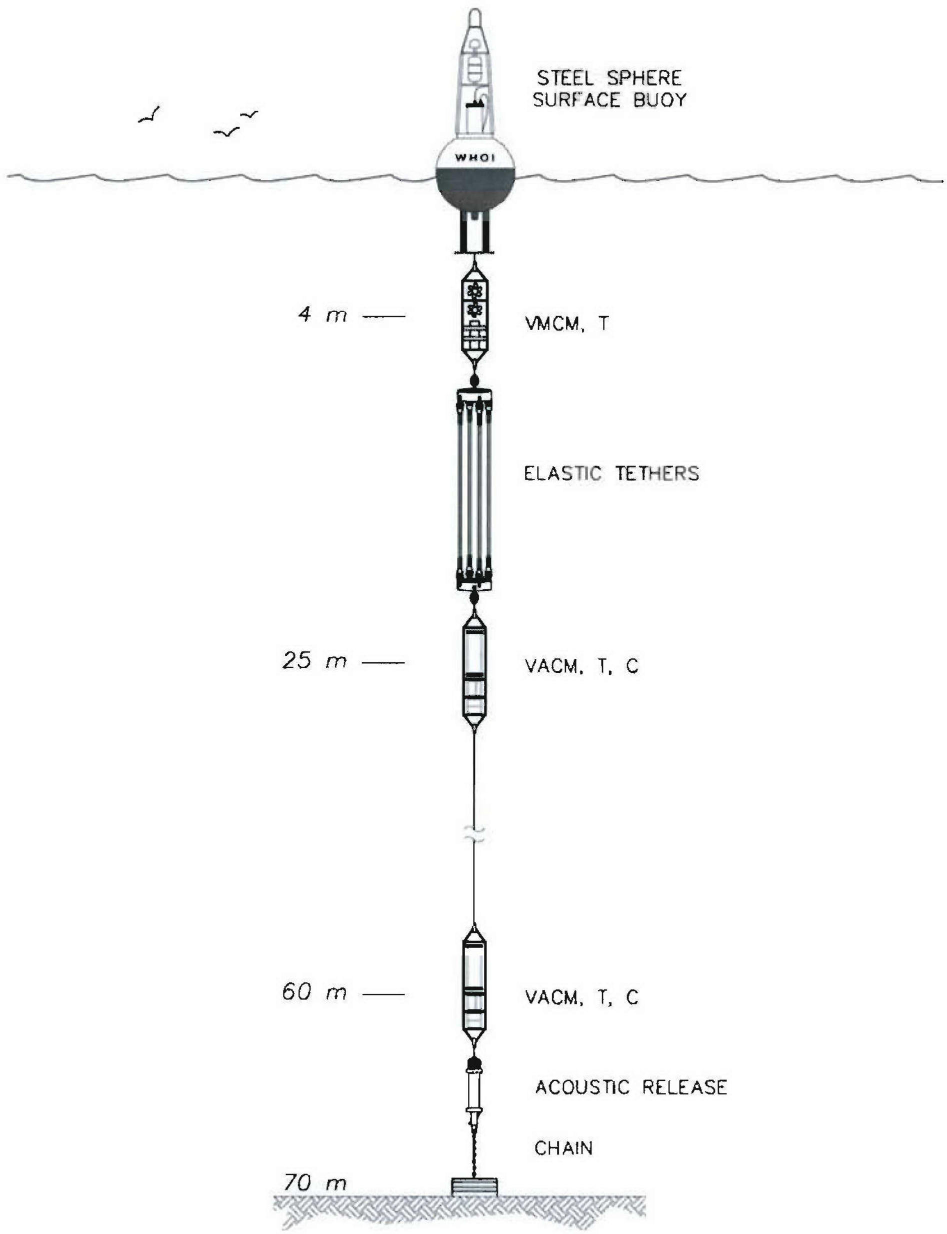

Figure 11. Massachusetts Bay Current Meter Mooring configuration with the compliant elastic tether located between the surface measuring current meter just below the buoy and the VACMs located lower in the water column to prevent mooring motion from contaminating the VACM records.

Typically a mooring using elastic tethers is designed with a mean stretch of 100% (the length of the mooring at mean tide with no waves or currents), and the length of the tethers is selected so with expected currents, tides and waves, the stretch of the tethers is in the 50 to 150% range. It can easily stretch from 10% to 200% under more sever conditions. Under unusually severe conditions, the tethers can stretch several 100% without damage or failure (Figure 12). A single tether provides 85 lbs of tension at 100% stretch, and will break before it reaches 800 lbs tension. The tether must not be allowed to go slack (tension going to zero), because the elastics may then

tangle in the mooring/bridle and be damaged (cut or nicked so that premature failure may result). Tethers are not as durable as chain or stretch hoses as they are made of rubber without abrasion, or cutting resistance. Therefore, they are more subject to "fishermen bite" than chain catenary or stretch hose moorings, since they are fairly easily cut by fishing gear. Tethers have survived North Atlantic winters without problems, and only to fail in the spring when the good weather and calm seas arrive (with fishermen). Also, a mooring with elastic tethers must have a swivel in line so that the tether assembly does not twist up and prevent all the tethers from sharing the load equally. The one mooring failure that was attributed to a tether assembly breaking was when a swivel was reused without being checked, and when recovered it did not freely turn and was probably the cause of the failure.

With the compliance at the bottom of the mooring (provided by chain catenary, elastic tether or rubber hose), instrumentation on the mooring line below the buoy must be accelerated upward by the buoy as it follows the wave field. With large numbers of instruments (and weight) in the mooring line, the shock loading as the buoy starts to move upward while the mooring and instruments are still moving downward can easily get above 10,000 lbs. As the tensions in a chain catenary mooring tend to be larger because heavier mooring components are used, which makes the shock loading worse for the chain catenary mooring. Adding a depressor weight near the bottom to make the chain catenary mooring more vertical for better environmental observations, but makes the shock loading tensions in the mooring even higher, as this weight must be accelerated by the buoy moving with the waves as well. This added forces due to the buoy having to accelerate the mooring (all subsurface components) affects the buoy motion (i.e making it more difficult to be a good wave follower) - as anyone who has climbed aboard a buoy at sea knows.

An elastic tether mooring providing compliance reduces the need for a depressor weight, allows lighter components to be used in the mooring itself, and thus reduces the shock loading. By not having to accelerate the mass of chain providing the compliance in the mooring, the elastic tether further reduces the shock loading. As an example of this, see the discussion given in the modeling section below.

2.3.4. Experience: The tethers used on the environmental monitoring mooring in the coastal Gulf of Maine (Figure 10) have been deployed for three years with quarterly servicing. The elastics and splices appear to be in fine shape, and will continue to be used until degrading of performance or appearance is observed. These elastics were deployed in GLOBEC for 6 months before being used in the environmental monitoring mooring, so have seen considerable usage. The elastic tethers deployed in GLOBEC were used until they were damaged by fishing activities or recovery operations, or were stretched so the splices slipped by unknown reasons (Irish, 1997 and 2000) – none lasted more than 18 months. In the Gulf of Maine (Wood and Irish, 1987) and in Massachusetts Bay (Geyer et al., 1992) the tethers were deployed for one year or more. In the Gulf of Maine, the depth was incorrectly read from the Precision Depth Recorder (improperly corrected for transducer depth), and the moorings were deployed with tethers stretched at slack water to about 200%. The tethers worked well, but after recovery, the tethers were observed to have taken a permanent elongation of 2-3%. It is critical that the tethers be deployed with a known elongation, so that the depth of the deployment must be well known, and the design made for that depth, and care must be made to assure that it was deployed as close to that depth as possible. This requirement does not allow one to easily change the mooring depth at sea after a

local survey is completed, or when it is discovered that a previous survey or chart of the desired site is not accurate.

One set of elastics recovered from GLOBEC had some small checks, or cracks in the rubber where it went around the thimble. To test if this degraded the strength of the tether, it was taken to a gravel pit and pulled to about 5 times its original length of 10 meters with over 750 lbs tension (spring scale pegged so exact tension was unknown). There was no more space to stretch the tether farther, and the tether did not break (Figure 12).

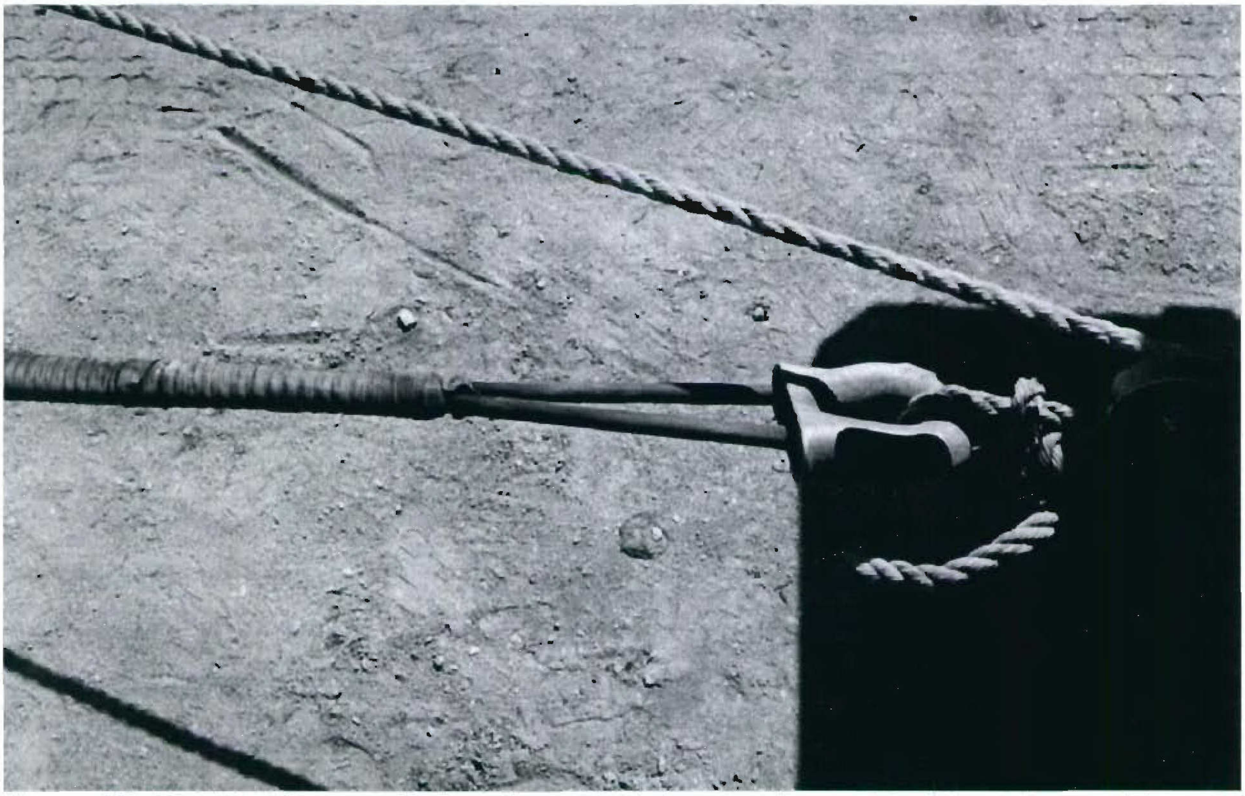

Figure 12. Elastic tether stretched to about 500% showing the stretch of the splice, and the thinning of the elastic under tenson. This is a GLOBEC tether after a year of deployment with slight checks observable in the rubber. In this case, the checks did not degrade the performance of the tether.

Sunlight can also damage the components in the splice. Figure 13 shows a tether from GLOBEC that was pulled hard enough that the splice slipped significantly. When tension was removed upon recovery, the splice curled up into this small circle. As a test for sunlight damage, this tether (and several others) were placed on the roof of a van on Dyers Dock in Woods Hole, MA for about a year, fully exposed to the atmosphere, sun and weather. The degradation of the self-vulcanizing tape on the surface of the splice can be seen, but the lower layers of tape still held the splice tight – although not usable. However, this damage was from a year exposure, so exposure for a day or two should not be a problem. The rubber material itself appeared undamaged, but no tests were made to determine if the properties had changed.

Figure 13. A tether from GLOBEC that has been pulled so that the splice slipped. When the tension was removed, the splice curled up in a 360-degree circle. The tether rubber, remains under high tension around the thimble. This splice was then left out in the sun and weather for a year, and shows the degradation of the rubber tape with sunlight.

2.3.5. Numeric Modeling: To utilize either of the compliant technologies (hose or tether) and to a lesser extent the chain catenary, good modeling of the mooring, environmental conditions, and especially the compliant component is required to construct a viable mooring. To compare chain catenary and elastic tether configurations for a mooring on the crest of Georges Bank in about 45 meters of water, modeling of these two moorings was done using WHOI Cable (Gobat et al., 1997). Various currents and waves typical for the Georges Bank region were input to modeling the chain catenary (Figures 1) and compliant elastic (Figure 8) moorings (Paul et al., 1999). The results illustrate the differences in behavior between these two mooring techniques. Figure 14 shows the horizontal movement of the buoy and mooring position in the water column with currents ranging from 0.1 m/s to 2.0 m/s. The elastic tether mooring (Figure 14, top) is taut, with all the mooring components always suspended in the water column off the bottom. This allows for the use of lighter weight mooring hardware that does not need to survive dragging about on the bottom. The chain catenary (Figure 14, bottom) has a larger watch circle because of the amount of chain required on the bottom to supply the necessary compliance, and heavier

mooring hardware that is required for that part that drags on the bottom. As the current increases, the elastic tether mooring continues to stretch with the increasing drag, but still has additional stretch to allow the buoy to move up and down with the waves. To make the mooring stiffer, a greater number of tethers should be used to increase the mooring tension. At maximum current modeled (2 m/s), the chain catenary mooring has stretched out the chain so that it is almost all off the bottom (Figure 14, bottom), and the mooring cannot deliver much more compliance to allow the buoy to move with the waves and the tension rises sharply at each wave crest.

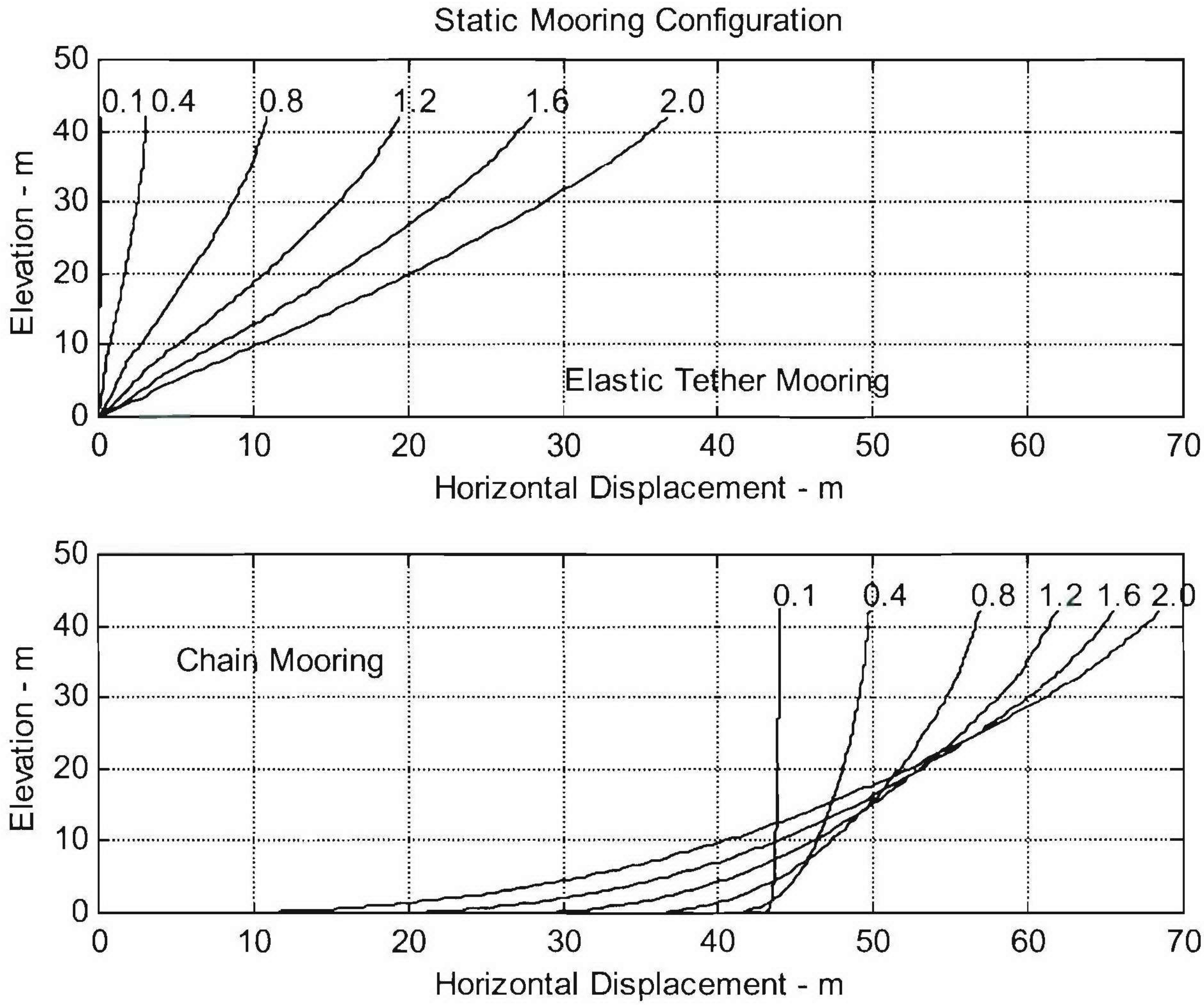

Figure 14. WHOI Cable simulation of an elastic tether mooring (Figure 8) and a chain catenary mooring (Figure 1) with currents of 0.1 m/s to 2 m/s showing the difference in mooring shape and the reduction of the compliance in the chain catenary mooring

The tension time series at the buoy is shown in Figure 15 with 7.5 meter 12 second wave forcing along with 1.6 m/s currents. The peak tensions in the chain catenary mooring are about 3 times as large as in the compliant elastic tether mooring. Part of this extra tension in the chain catenary mooring is due to the additional weight of the mooring components that must be accelerated by the buoy. The lower tensions in the tether mooring also allows lighter weight mooring

components to be used, thereby reducing the shock loading even more. The observed tensions are in line with those observed on the elastic tether deployed on the Crest of Georges Bank with forcing similar to that modeled (Paul et al., 1999). Stronger currents will cause the tensions in the chain catenary to increase faster than in the elastic tether under the same wave forcing because of the loss of compliance as the chain catenary mooring is stretched out.

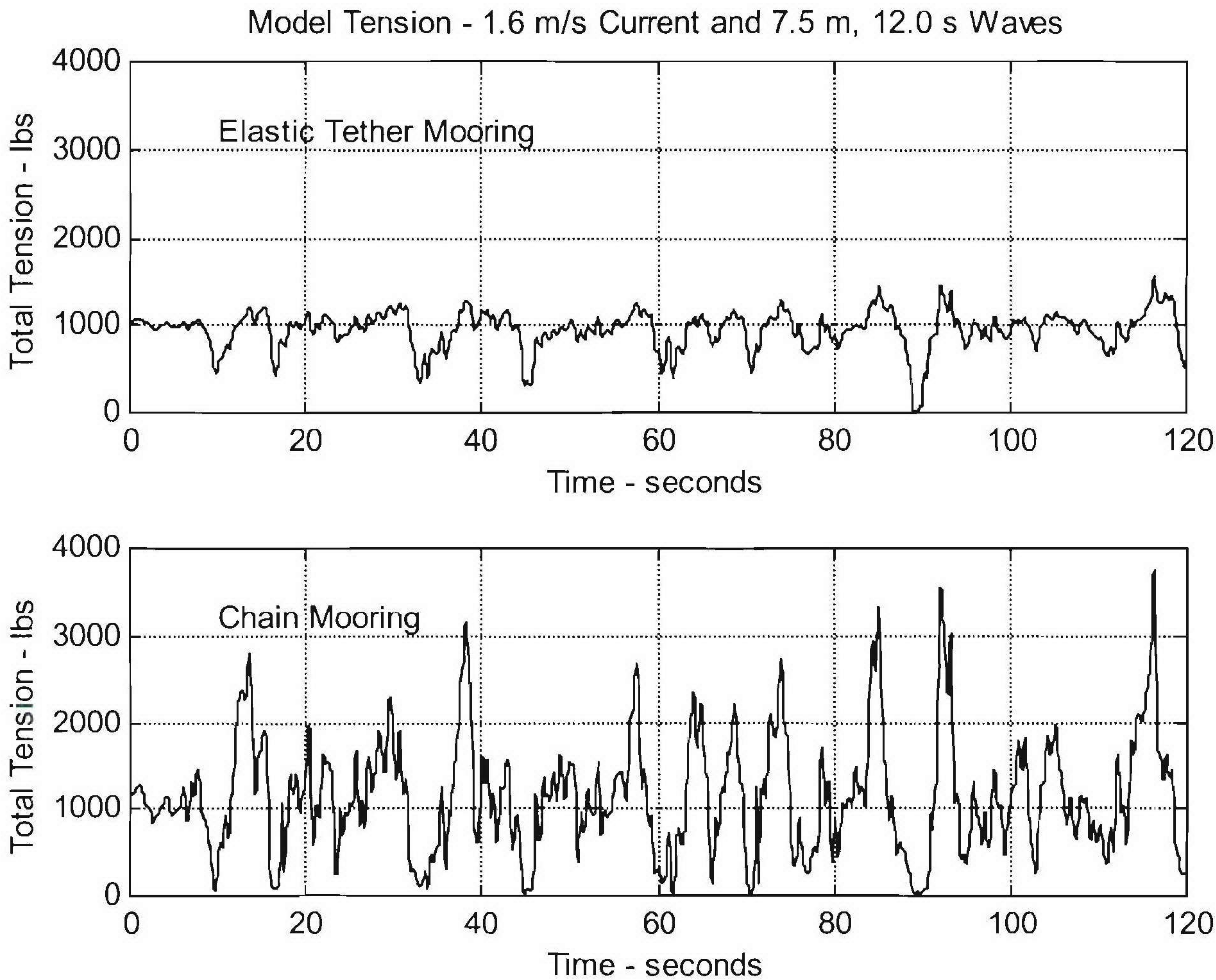

Figure 15. Mooring Tension time series at the buoy from WHOI Cable modeling of the elastic tether mooring in Figure 8 (top) and standard chain catenary mooring in Figure 1 (bottom) showing the higher shock loading in the chain catenary mooring with wave forcing.

Often a depressor weight is added to a chain catenary mooring near the bottom in order to make the mooring stiffer. To model these effects in the case discussed above, a 1,500 lb. depressor weight was added at the bottom of the ½" chain where it changed to ¾' chain for compliance along the bottom in Figure 1. This depressor weight has often been used by WHOI in 3 m discus buoys in coastal waters. Applying the same 1.6 m/s mean current and 7.5 m 12 second waves, the tensions are much larger. A section of the simulation with the tensions at the bottom, at the depressor weight and at the buoy is plotted in Figure 16. The peak tensions are regularly above 8,000 lbf. at the buoy and nearly as large at the anchor. In the simulation the buoy was forced to follow the surface, and the anchor was fixed to the bottom, so there is no possibility of sinking

the buoy or moving the anchor. However, the high tensions show the problem of having to accelerate large masses on the mooring as the buoy follows the waves.

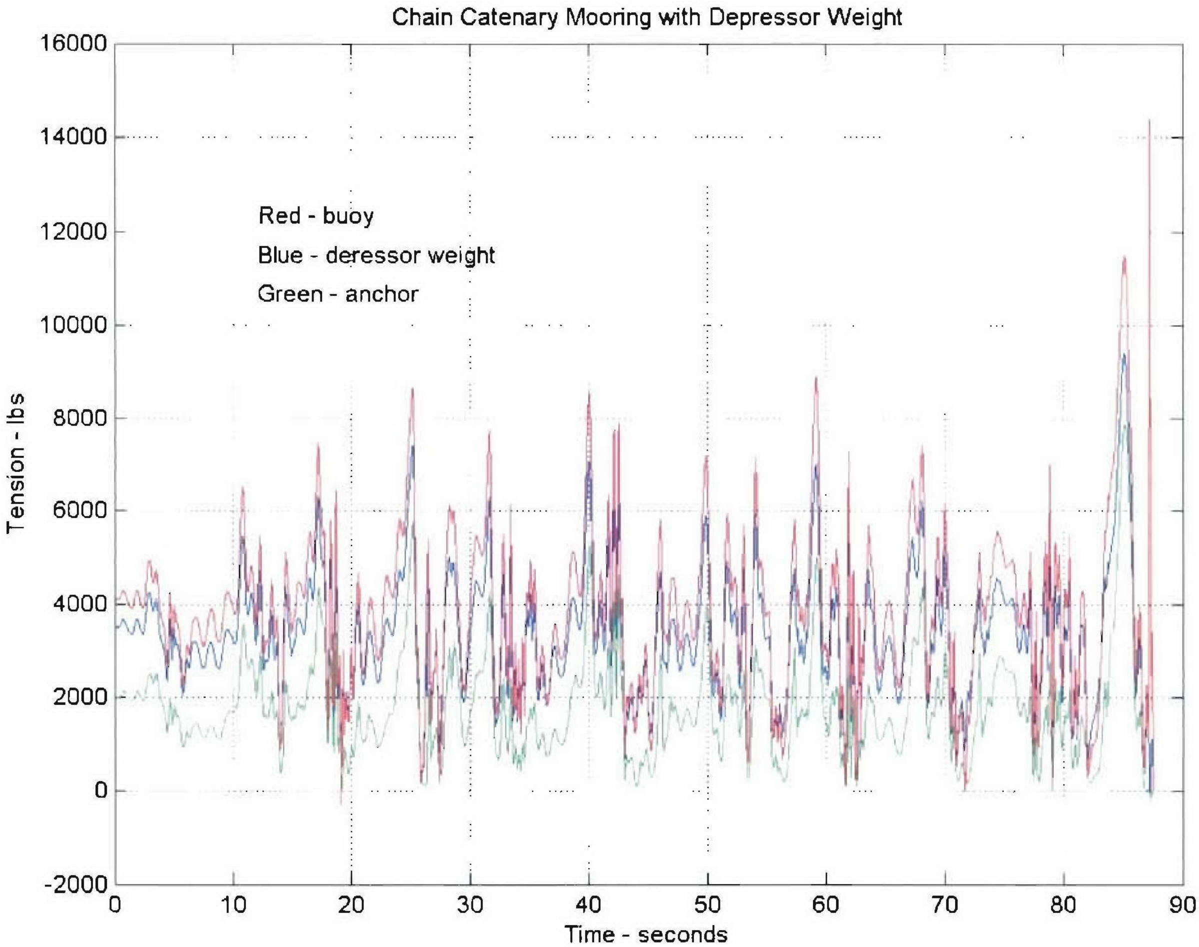

Figure 16. Chain catenary mooring (Figure 1 configuraiton) with 1,500 lb depressor weight located between the ½" chain and the ¾" chain to keep the mooring more vertical.

The focus of this rest of this report is on the behavior of the compliant elastic tether components in controlled laboratory tests/evaluations. The elastic modulus is the quantity that specifies the material properties to the modeling programs. Buoy Technology Inc., conducted a study of the stress - strain relationship of the Natsyn tether material in January 1977, and estimated of the modulus to be around 123 psi (see discussion and Table 4 below). This study was done in a high bay with a short section of elastic, and at strains of less than 200% in a static condition. The new tests reported here varied the test conditions considerably. The tethers were pulled out to an average stretch of 100 to 250%, then cycled about this stretch to simulate the conditions on a mooring at sea (initial stretch for static condition, and then additional stretch around this static condition with waves and tides).

3.0. Elastic Tether Testing Setup and Testing:

3.1. Elastic Modulus for Rubber Materials: To characterize the stretch characteristics of the rubber used in making the mooring tethers, it is useful to determine the effective elastic modulus from test data of the cycled rubber tethers. This result can then be input into numerical mooring modeling programs like WHOI Cable to design viable moorings. With known load and elongation data from the tests discussed below, the elastic modulus can be calculated.

The elastic modulus, E, of materials under tension is the ratio of the unit stress, σ, (equal to the tension divided by the test sample's cross sectional area at zero tension) to corresponding unit strain ε (expressed in % elongation/100),

$$E = \sigma/\varepsilon. \qquad \text{Equation 1}$$

For rigid engineering materials characteristic values are obtained over the large useful stress range of the material. The test sample's strain grows proportional to the applied stress, with a constant rate – the modulus. This is not true of rubber (and textile) material, where the proportional relationship between stress and strain is constant over only very small elongations. Rubber becomes stiffer with increasing elongations so the modulus will increase. For larger elongations the modulus of elasticity is best determined by measuring the slope (tangent) of small linear sections of the stress-strain curve. The elastic modulus value is only representative for the region in which it is measured, since the tangent does not necessarily intersect with the origin. The elastic modulus for the rubber material can be determined from

$$E(\varepsilon) = \partial\sigma/\partial\varepsilon = 1/A\ \partial\text{tension}/\partial\varepsilon \qquad \text{Equation 2}$$

as a function of strain (elongation) where A is the test sample's cross sectional area at zero tension. A modulus curve can be established over the entire strain range to characterize the material's behavior. Different elastic modulus values are found for increasing and decreasing elongations of the test samples, and a hysteresis curve is formed under cycling loads or extensions. (See MIL Handbook 149A, Rubber and Rubber-Like Materials, p. 7, Washington DC 1965.)

3.2. Setup: Tension Member Technology (TMT), Huntington Beach, CA, specialists in cable and rope performance testing, have equipment capable of cycling elastic tethers around different mean stretch lengths to determine the modulus under various conditions. A used and a new tether were terminated specifically for these tests. The tethers were terminated to an optimum length for use with the TMT equipment. That was a 16-foot section of Natsyn rubber terminated by wrapping around a bronze thimble, doubling the tether back on itself and attaching the ends with self-vulcanizing rubber tape. About 2 feet was used at each end for the splice, resulting in a splice free section of approximately 8 feet long. The length of the unstretched tethers from eye-to-eye was about 12 feet.

The two tethers were tested side by side at the same time on the same machine. One end of each was attached to the non-moving load frame of the machine via load cells (Figure 17). These load cells measured the tension in the tethers as a function of strain measured by the position of the other end of the tether. The tensions were logged by a computer controlled data acquisition system.

The other end of the two tether samples was attached to the crosshead of a linear drive mechanism (Figure 18). The position of the crosshead (and therefore the stretch of the tether)

was measured with a displacement transducer. The output of the displacement transducer was acquired by the data acquisition system and was scaled and biased so that the crosshead position measured was the thimble-to-thimble length of the tethers.

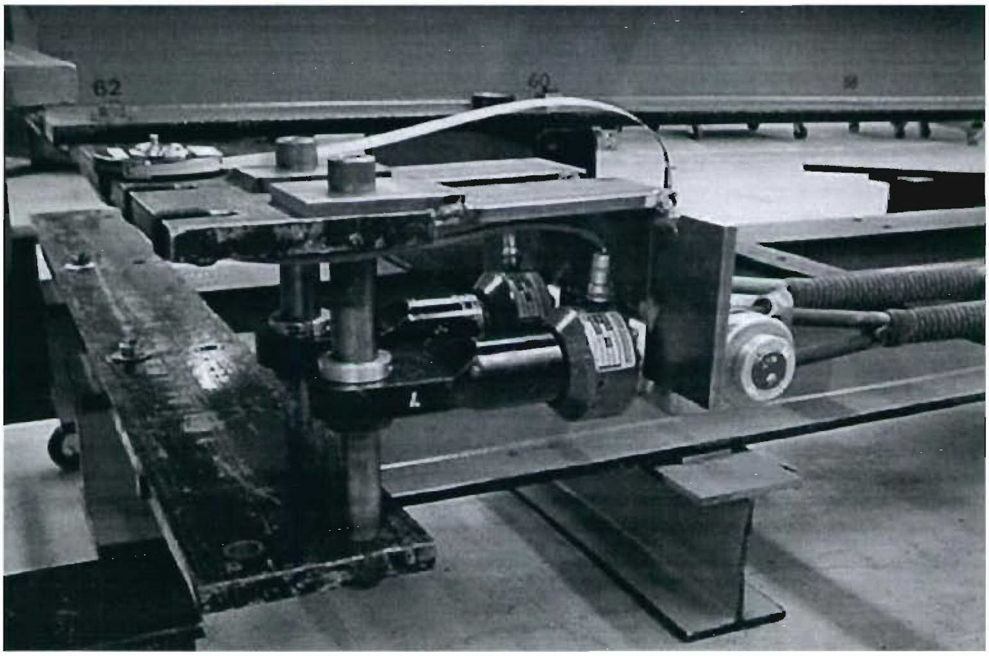

Figure 17. The two elastic tethers (right) are attached to the fixed end of the tensioning apparatus to load cells that measured the tension in each tether at a given elongation.

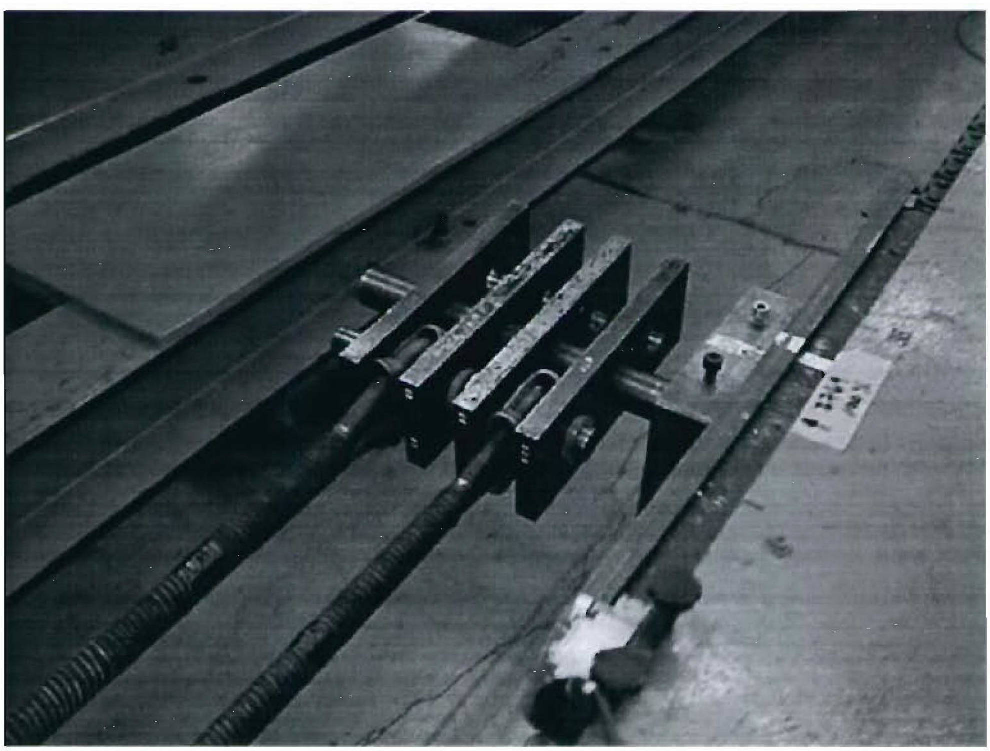

Figure 18. The other end of the tethers was attached to the crosshead on the tension machine.

The machine was run so that the tethers were stretched between specified limits (Table 1) for specific times (See Figure 19 for an overview with the space for movement of the crosshead seen). For each of the runs in Table 1, the minimum, center and maximum position were measured with a tape to make sure the elongation was as desired and was exactly known. Figure 20 shows a typical run of position of the crosshead versus time. The movement during a large part of the record was to allow measurement of the minimum, maximum and mean positions of the crosshead. Then the 10 cycles of the run were made at the end of the time.

Table 1. Dynamic Test Plan

TEST	TARGET STRETCH - %	CYCLES
T-1	75 to 125	10
T-2	50 to 150	10
T-3	125-175	10
T-4	100-200	10
T-5	175-225	10
T-6	225-275	10
T-4 Extended	100-200	3,000
Overnight Hold	100	1

Figure 21 shows the tension versus crosshead position. The hysteresis in the measurements, and the differences between the old and new tether samples is seen. Some of the difference between the new and old is due to the spliced lengths not being exactly the same, the different no-stretch cross sectional area (see Table 2) and some is due to the "aging" of the tether used in the ocean environment. However, the results are surprisingly similar, indicating the well-behaved properties of the elastic tethers.

Table 2: Tether dimensions at indicated stretch measured at three different places.

TETHER	DIAMETER BEFORE STRETCH	DIAMETER AT 10% STRETCH	DIAMETER AT 100% STRETCH
New	1.01 inches	0.997, 0.980, 0.995 inches	0.725, 0.739, 0.737 inches
Used	0.94 inches	0.883, 0.887, 0.895 inches	0.651, 0.656, 0.659 inches

4.0. Test Results:

4.1. Test T-1: The "typical" design stretch for an elastic tether assembly is about 100%, and a low excitation would be 75 to 125% (test T-1) or with more excitation, 50 to 150% (test T-2). The samples were mounted as discussed above, and then stretched to 75%, 100% and 125% and the distances measured (Figure 20). The system was then run for about 10 cycles. The velocity of the crosshead was set to about 1 foot per second in all tests to simulate a realistic vertical velocity of a buoy at sea. The tension and crosshead position time series were plotted to check

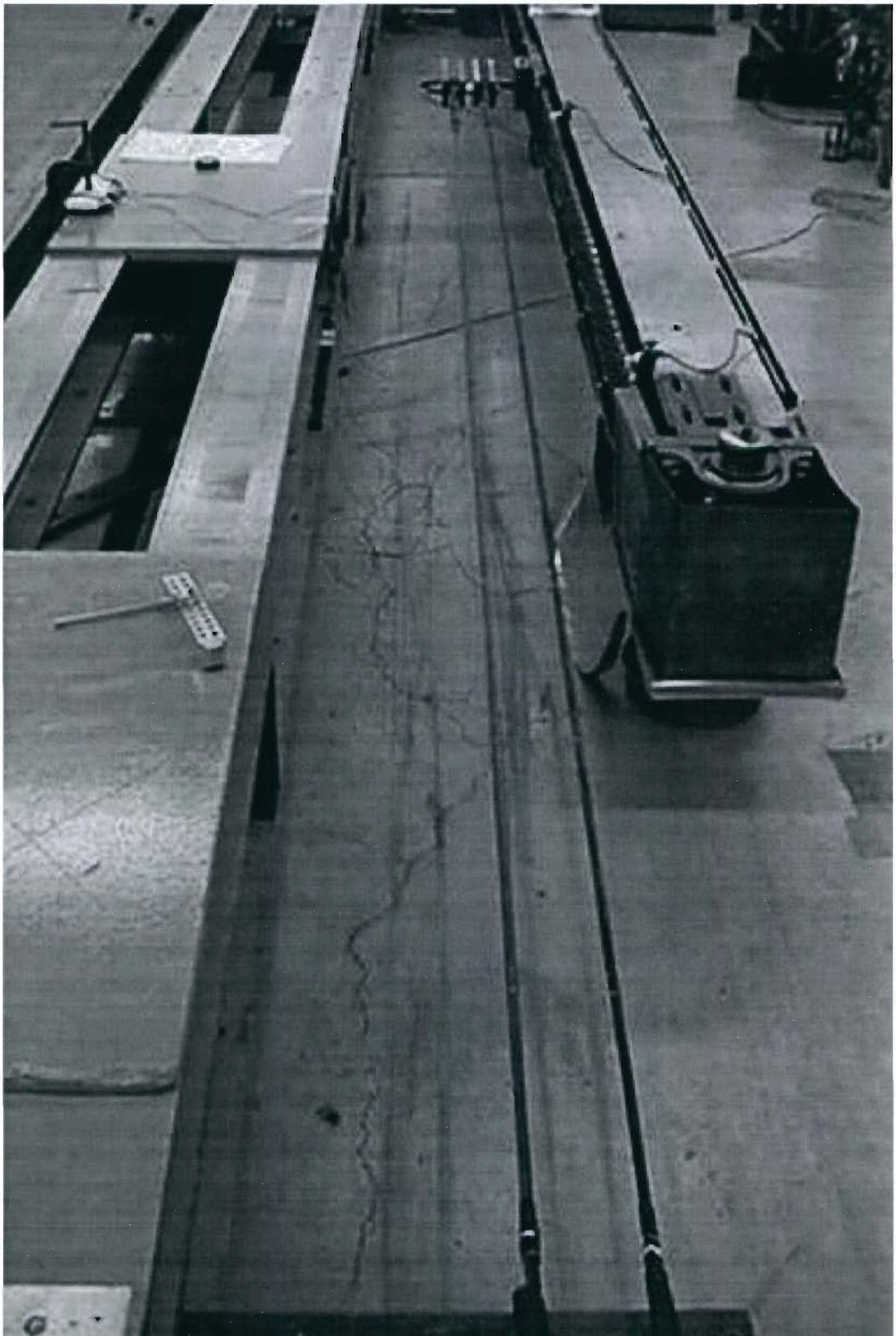

Figure 19. The tethers undergoing tests in the machine. The far end (crosshead) moves back and forth with the chain drive.

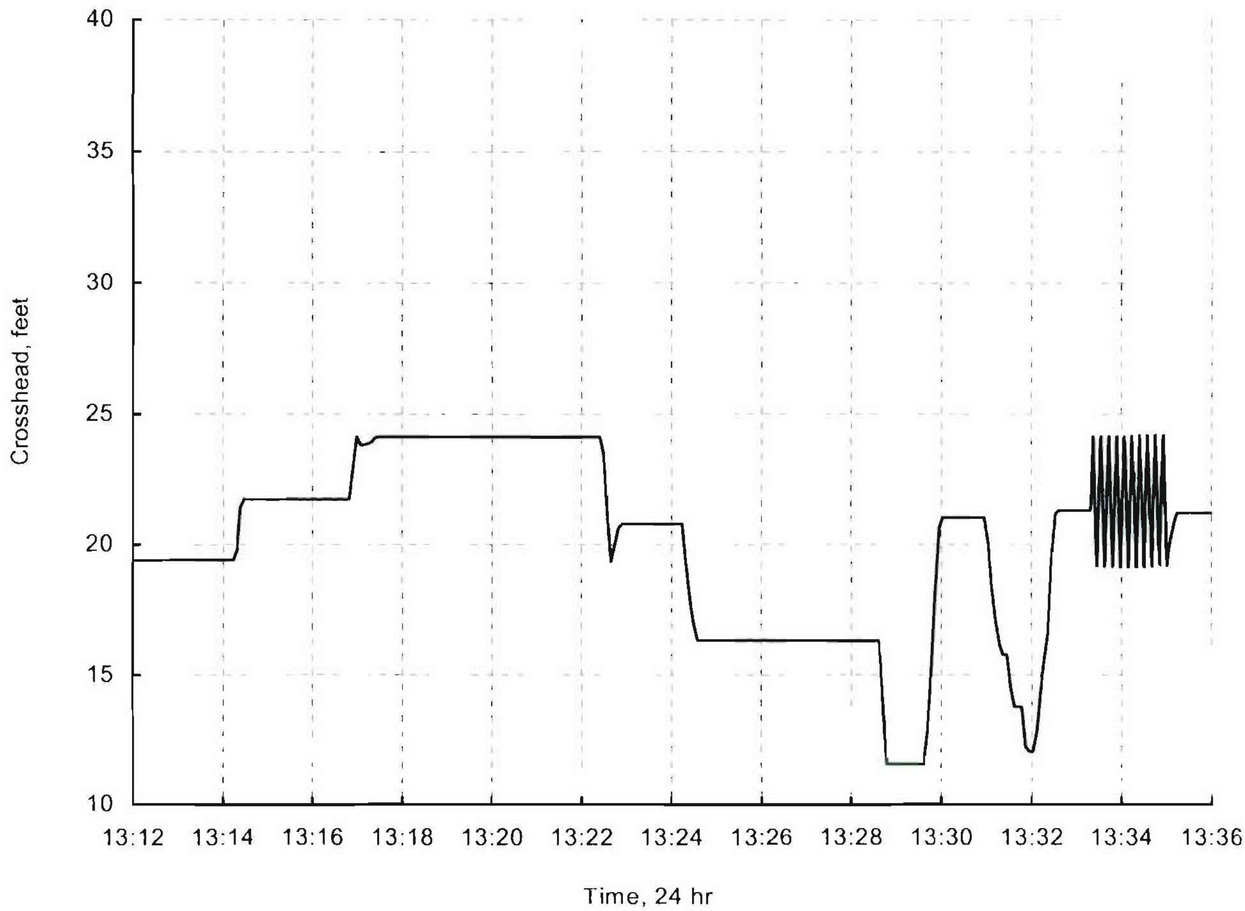

Figure 20. The time (bottom), versus crosshead position (strain) for test T-1. The ten cycles of the measurement (75 to 125 % elongation) are seen at the right.

the results (Figure 21). Tension Member Technology provided the recorded data in Excel spread sheets. The data was read into MATLAB and the modulus calculated from the 10 cycle sections at the end of each test by Equation 2. The cross sectional area of each tether was measured - pre-test diameters, 10% and 100% stretch diameters and listed in Table 2. Note that the pre-stretch diameters were used for calculation of the elastic modulus.

The modulus of the Natsyn rubber itself was desired, and not the tether including the splice. TMT painted white marks on the toe of each splice (see Figures 19, 32 and 33). The tether was stretched out to the desired crosshead position, and the actual distances measured, tabulated (an example for test T-1 is shown in Table 3), and the interpolated percent stretch of the free rubber section of the tether determined. This was used as the elongation in Equation 2 to determine the elastic modulus.

A difference from the Wyman test mentioned earlier, is that the tether was stretched to a given length by the test machine, then cycled about this mean elongation. This is different than adding a given weight (tension) and determining the amount of elongation. The TMT method was to stretch the tether out to the minimum, mean and maximum positions, mark that and then run 10 cycles between the maximum and minimum stretch points. When the tether is first stretched (particularly at higher tensions), the tension in the tether is a maximum and then it decreases with

time as the rubber relaxes. Sometimes this can be significant. For test T-6 (Figure 24), the new tether had a measured tension of 400 lbs when first stretched to 275%. Three minutes later, with the crosshead at the same position so the length (elongation) of the tether had not changed, the tension had dropped to 325 lbs. During the ten cycles, the tension of the maximum peak can be seen to still decreasing with time. This creep does stop after a time. During the last part of the T-4 extended test, the tethers were stretched to 100% and held for about 1 day. This was after cycling from 100% to 200% for 3000 times, and when the tethers were relaxed, they had no apparent change in tension over the day long hold, the tensions remaining constant ±1 lbf.

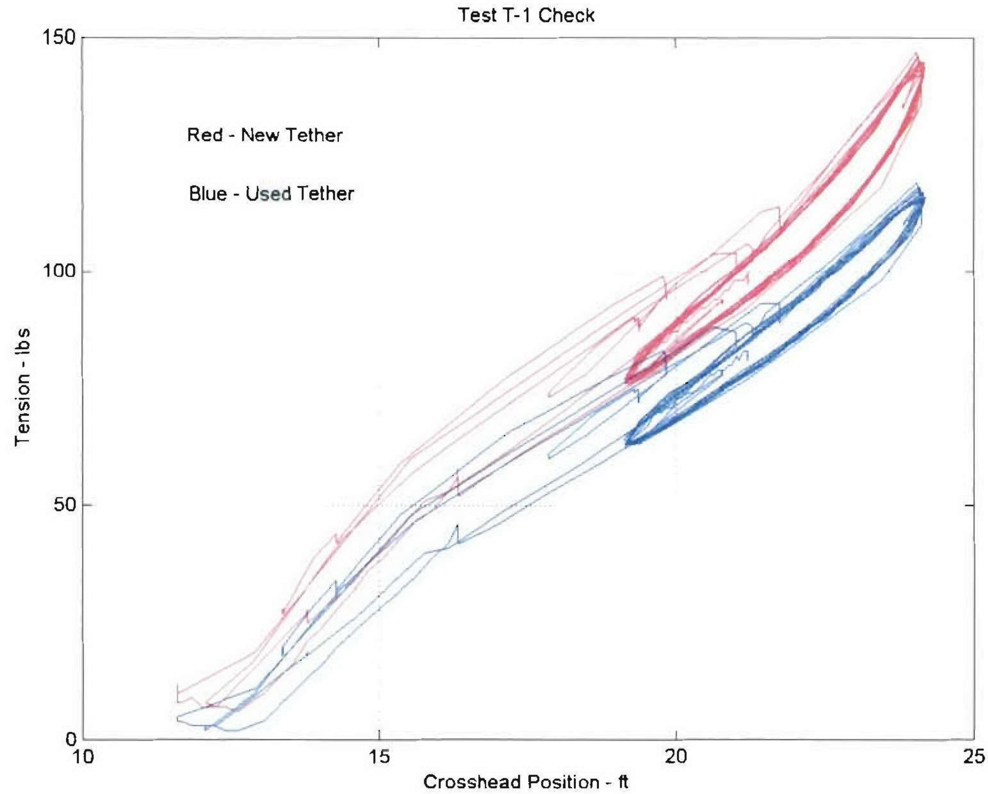

Figure 21. The tension versus crosshead position for test T-1 with the new tether in red and the old one in blue.

The results for the estimation of the elastic modulus for the new and used tethers from test T-1 are plotted in Figure 25 and plotted with the rest of the tests as a summary in Figure 31. The continuous cycling curves (e.g. Figures 22 and 23) were edited for the display as shown in Figure 15. When the elongation first starts to increase, the modulus is nearly constant, but as the elongation continues, the modulus increases. When the maximum elongation is reached and the elongation starts to slow and reverse, the modulus starts to drop, then as the elongation starts to decrease, the modulus jumps to a highest level and starts to decrease more rapidly, ending up below the increasing elongation curve. As the minimum elongation is reached, the modulus drops as the elongation reaches the minimum, then jumps up to a higher value that quickly returns to the smooth curve of the increasing elongation. For clarity of presentation in Figures 25 through 31, these end points have been removed from the plotted modulus versus elongation curves.

The modulus versus elongation curve (Figure 25) shows the expected hysteresis of the modulus during stretch and relaxation - The modulus is higher with increasing elongation and lower with decreasing elongation. With the ends cut off, the typical continuous hysteresis curve (such as suggested by Figures 22 and 23) is not obtained as we are examining the slope or derivative of these curves. The basic shape of the modulus versus elongation curve does not change over the duration of the cycles. Ideally, the modulus should be a constant with elongation, implying a linear stretch to tension relationship as normally expected by metals, and expressed by equation 1. For the elastic tethers, the elastic modulus is non-linear for most of the cycle, increasing with increasing tension and elongation, and changes only slightly with the number of load cycles applied. The used tether's results agree well with the new tether's, indicating no significant change in properties with use at 100% mean stretch.

Table 3: Calculation of stretch of splice free length of cable for test T-1.

New										actual	interpolated
	measured position, ft			length, ft			percent of total length, %			stretch, %	stretch, %
% stretch	near toe	far toe	far thimble	splice1	free length	splice2	splice1	free length	splice2	free length	free length
0	2.06	10.44	12.26	2.06	8.38	1.82	16.8	68.4	14.8		
75	2.42	17.22	19.37	2.42	14.8	2.15	12.5	76.4	11.1	76.6	79.7
100	2.53	19.48	21.75	2.53	16.95	2.27	11.6	77.9	10.4	102.3	101.8
125	2.69	21.72	24.12	2.69	19.03	2.4	11.2	78.9	10.0	127.1	123.8
						avg:	11.8	77.7	10.5		
Used										actual	interpolated
	measured position, ft			length, ft			percent of total length, %			stretch, %	stretch, %
% stretch	near toe	far toe	far thimble	splice1	free length	splice2	splice1	free length	splice2	free length	free length
0	2.04	10.38	12.26	2.04	8.34	1.88	16.6	68.0	15.3		
75	2.38	17.17	19.37	2.38	14.79	2.2	12.3	76.4	11.4	77.3	80.8
100	2.47	19.43	21.75	2.47	16.96	2.32	11.4	78.0	10.7	103.4	103.0
125	2.6	21.69	24.12	2.6	19.09	2.43	10.8	79.1	10.1	128.9	125.1
						avg:	11.5	77.8	10.7		

4.2. Test T-2: The test was run again with the mean elongation of 100%, but with an increased range of 50% to 150% elongation. The results (shown in Figure 26 and in the summary Figure 31) are similar to those of test T-1, but here the modulus remains constant for a larger part of the cycle, indicating that the elastic tethers are behaving linearly in this region. Again the new and used tethers have essentially the same results and the modulus from test T-2 overlap those of test T-1 (but being slightly lower around 100% stretch, and higher at the minimum and maximum elongations. That they are essentially the same indicates that no strange behavior is occurring.

4.3. Test T-3: Tests T-3 is similar to test T-1 with the mean elongation increased to 150% and the cyclic elongation is between 125% and 175% elongation. There is now a difference in the modulus (Figure 27) of the new and used elastic tethers at higher elongations, with the modulus being higher for the new tether, but the modulus for both elastic tethers is the same at the minimum elongation.

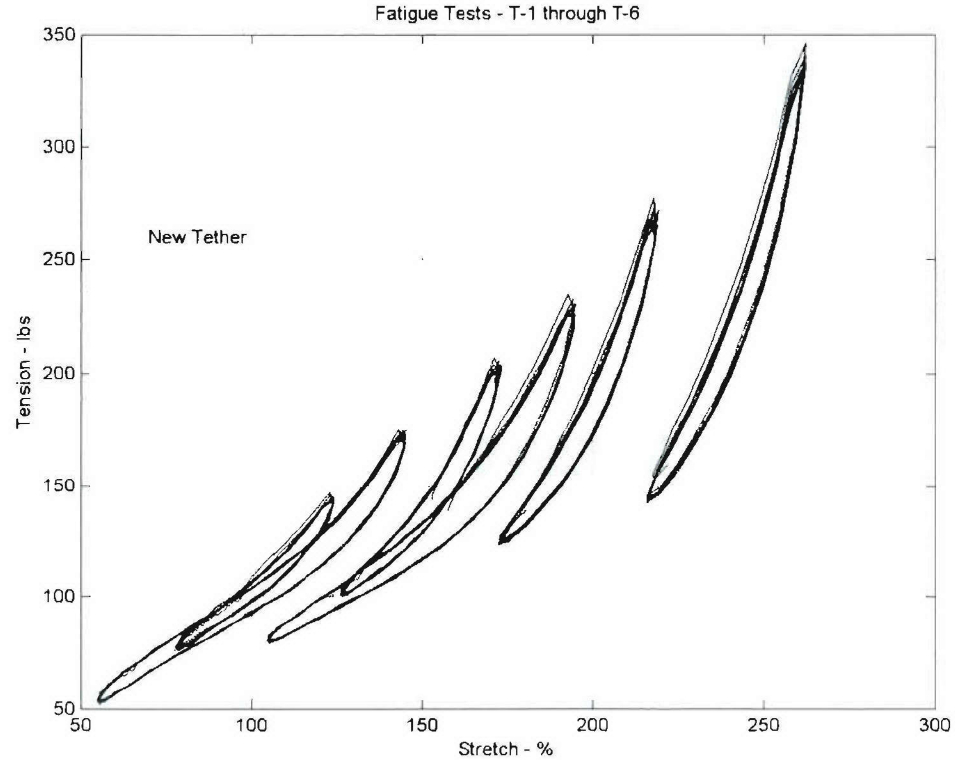

Figure 22. New Elastic Tether Tension versus Elongation for tests T-1 through T-6

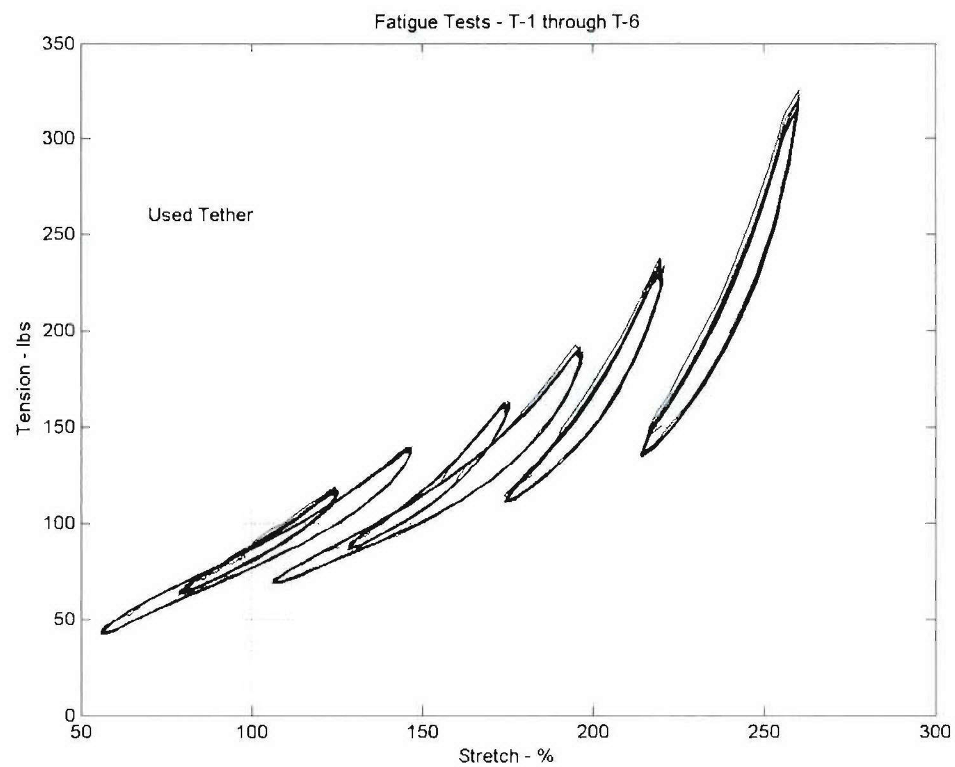

Figure 23. Used Elastic Tether Tension versus Elongation for tests T-1 through T-6

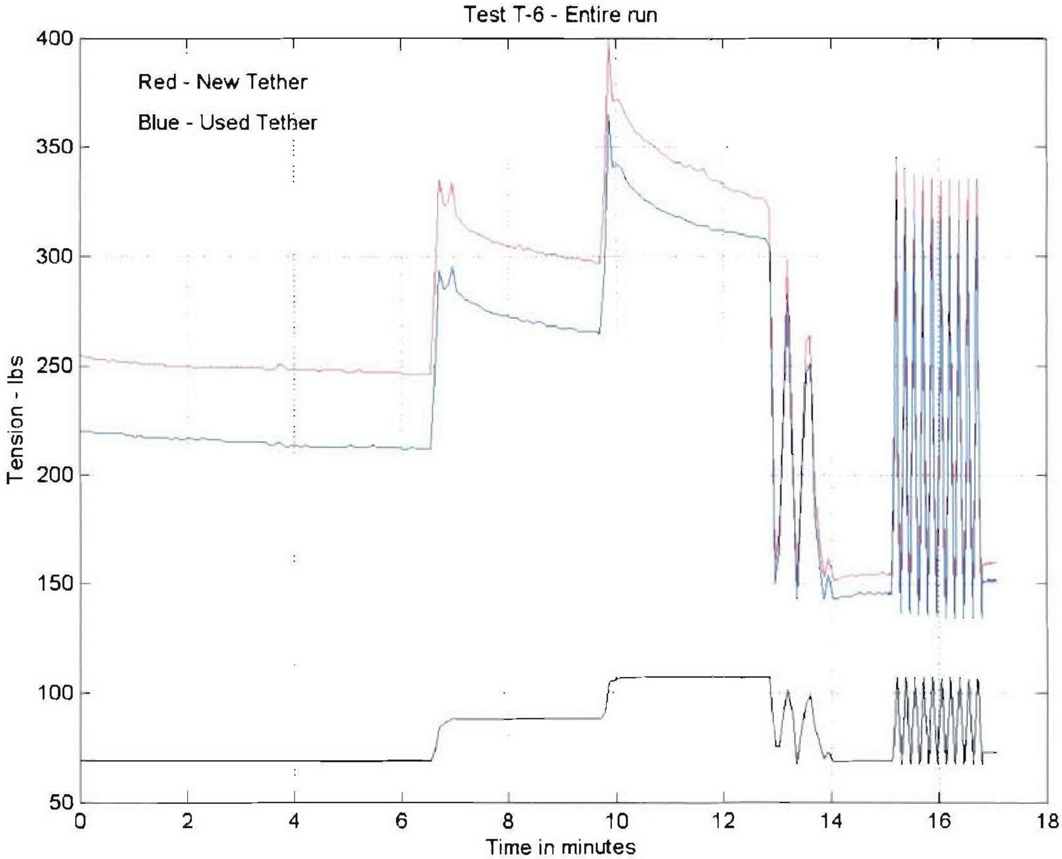

Figure 24: The T-6 run with a 275% maximum stretch showing the drop in tension in the tether when it is first stretched out. A plot of the scaled crosshead position (calculated by multiplying the crosshead position by 8 and subtracting 200 so that it looks good on the plot) is shown under the tension plots for comparison. The drop in tension at 275% is significant.

4.4. Test T-4: Test T-4 has the same mean elongation as T-3, but an expanded range of 100% to 200%. The modulus (Figure 28) for the new elastic tether is again higher at the maximum elongations, but the same at minimum elongations. The modulus at the minimum elongation is similar for tests T-1 through T-4, but the maximum modulus near the maximum elongation is higher for higher elongations.

4.5. Test T-5: For test T-5, the mean elongation was increased to 200% and cycled between 175% and 225% elongation. The new tether (Figure 29) has a slightly larger modulus than the used at higher tensions, but they are essentially the same at lower elongations.

4.6. Test T-6: For test T-6, the mean elongation was 250%, and the elongation range of 225% to 275%. This was the maximum stretch permitted with the test setup shown and discussed above. The modulus (Figure 28) from the used tether is now above the modulus for the new tether at all elongations. This is different from the results from tests T-1 through T-5, where the two elastic tethers were essentially the same. From looking at the results, we would have expected that the splice slip (discussed below) occured before this test, except that observations from the operator say that it slipped later during the T-4 extended test. The behavior of the two tethers is similar,

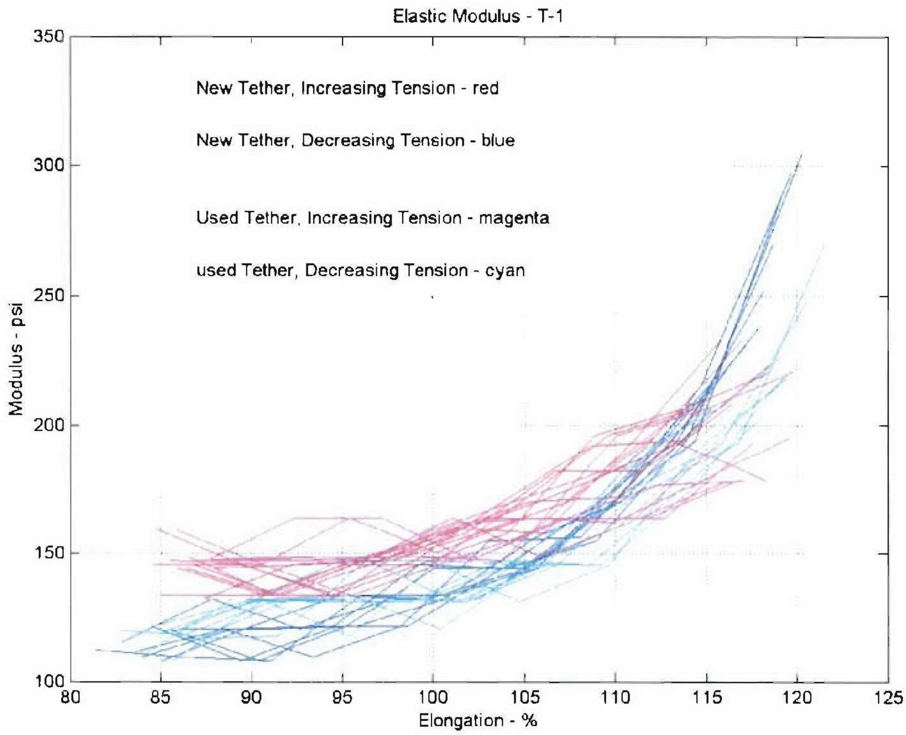

Figure 25. Elastic Modulus Versus Stretch for T-1.

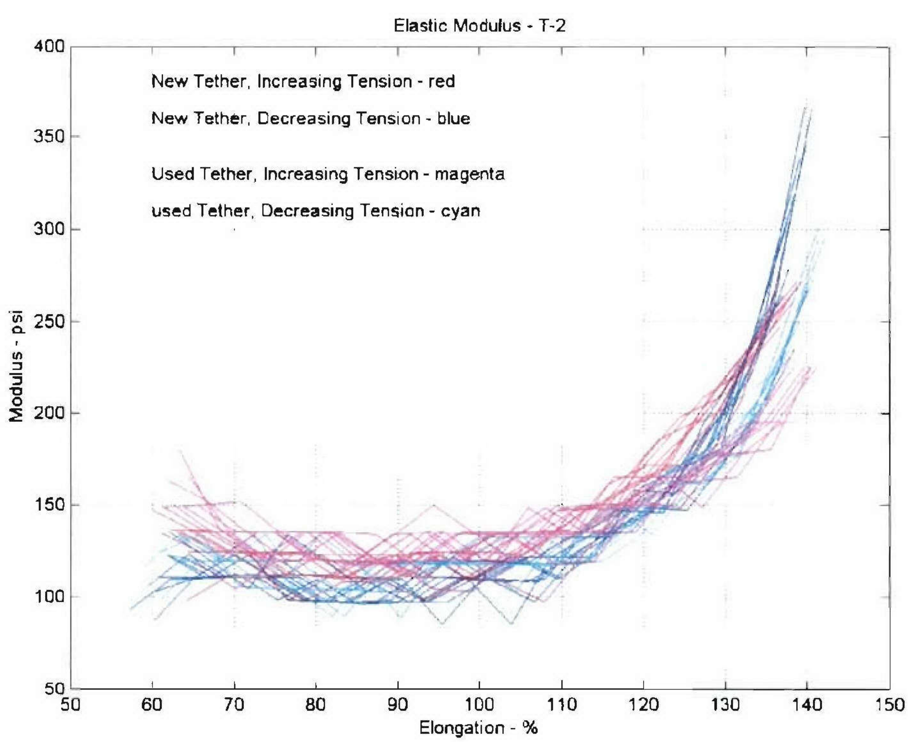

Figure 26. Elastic Modulus Versus Stretch for T-2

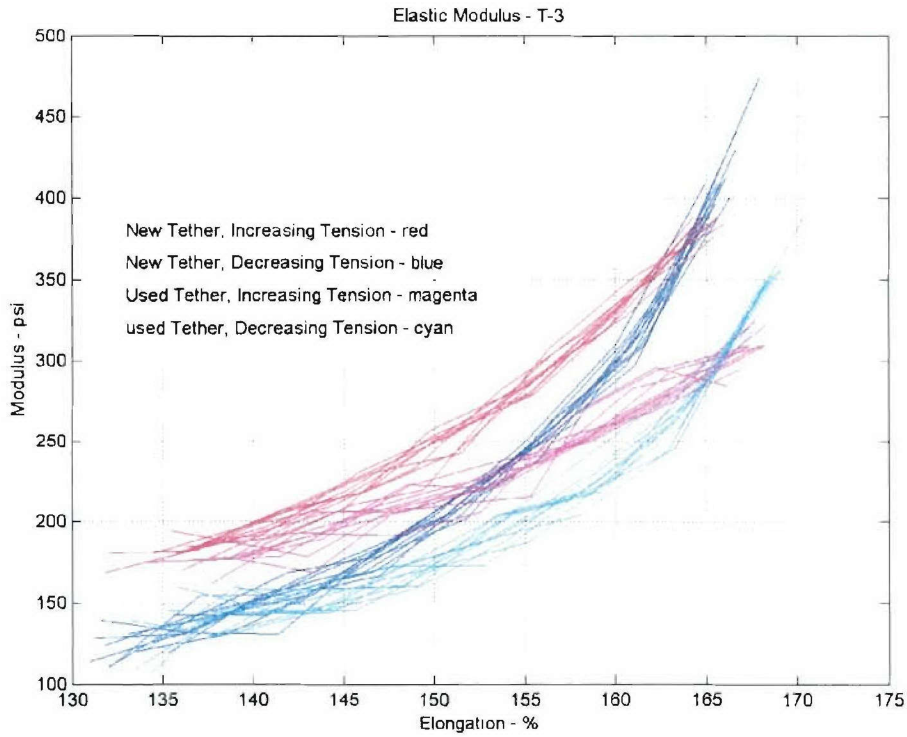

Figure 27. Elastic Modulus Versus Stretch for T-3

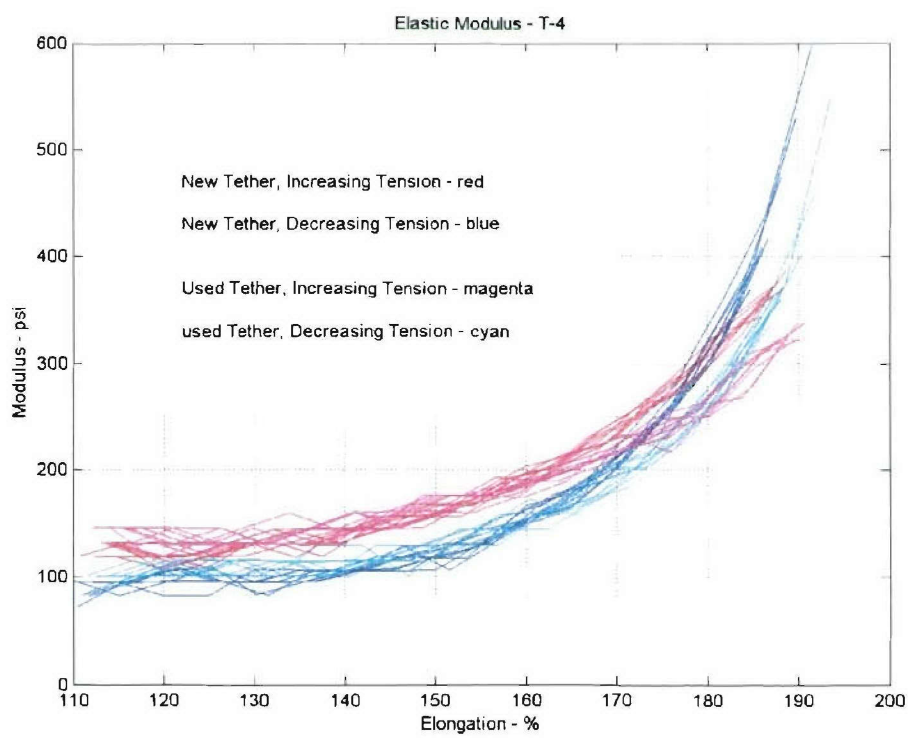

Figure 28. Elastic Modulus Versus Stretch for T-4

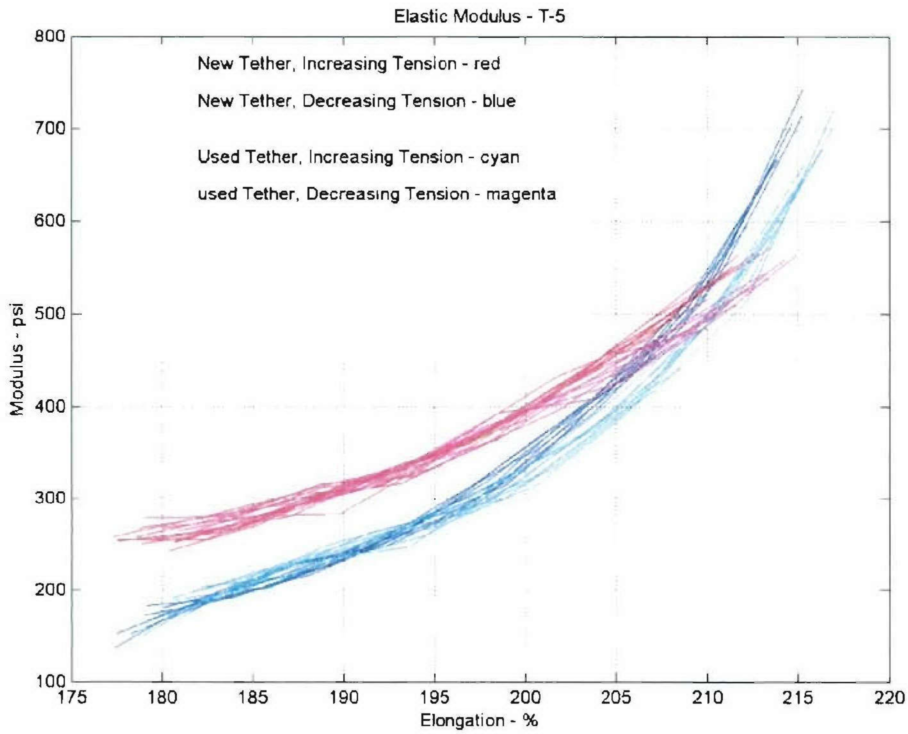

Figure 29. Elastic Modulus Versus Stretch for T-5

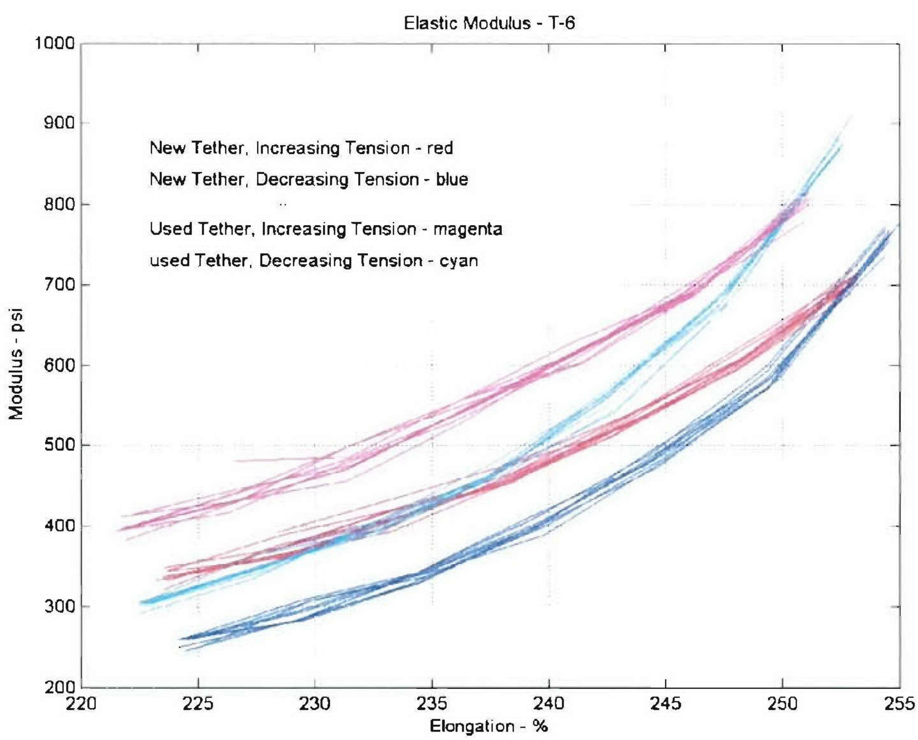

Figure 30. Elastic Modulus Versus Stretch for T-6

with the modulus being higher than earlier tests with the higher elongations.

A summary of tests T-1 through T-6 is shown below in Figure 31 for visual comparison of all 6 modulus versus elongation curves. In general, the two tethers appear to behave nearly the same except for T-6 around 250 percent. The new elastic tether has a higher modulus than the used one at higher elongations. The mean modulus increases with elongation over the range of elongations. The modulus has a greater slope with elongation as the mean elongation increases. The maximum modulus increases with increasing elongation. Except for test T-6, the observed differences in the new and used tethers are small, and probably not statistically different.

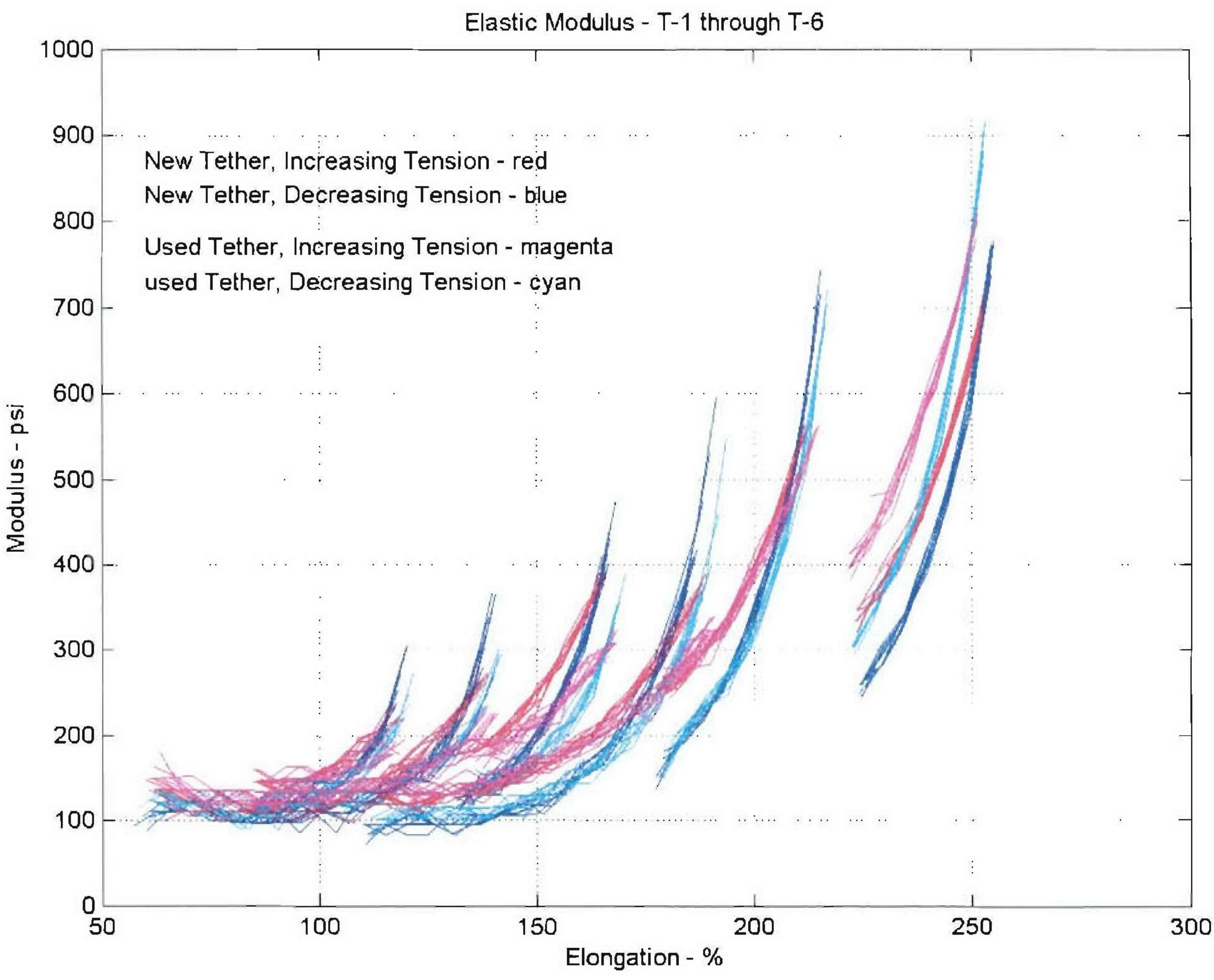

Figure 31. Elastic Modulus Versus Stretch, summary of T-1 to T-6

4.7. Test T-4 Extended 3000 Cycle Test: To further explore the behavior of the two tether samples, an extended test was run with the tethers stretched between 100 and 200% (similar to test T-4) for 3,000 cycles over a 16-hour duration (at a rate of 3 cycles per minute). However, a problem occurred during the extended test. The splices slipped and the termination tape tore (see Figures 32 and 33). This is typical of the case where the elastic tether has been pulled greater than 300 percent and the splices slipped. However, during all the tests conducted at Tension

Member Technology the stretch was less than 275% so no ship in any splice was expected. This, in part, accounts for some of the difference between the start of the test and end of the test results for the new tether shown in Figure 34. It is interesting that at the start, the new and used tethers show different moduli that do not overlap. This is similar to the results at 250% elongation in T-6, but not seen during T-4 when the elastics were cycled over the same range. The used elastic tether is essentially the same at the start and end of the test (blue and green curves) and the used splice does not show the slip seen in the new one (Figures 32 and 33). The new elastic tether also shows essentially the same modulus at the start and the end of the test. That there is not a change between the start and the end tends to support the hypothesis put forward in the discussion of test-T6 that the splice slipped during the setup for test T-6 and not during the extended test that followed immediately after test T-6. Also, that the moduli for the new tether is below that of the used tether (as in test T-6) also indicates that this slip in the splice may have started earlier than noticed in the log.

4.8. Comparison of Static test with Dynamic results: Buoy Technology, Inc. conducted a static test of the tether properties to determine the modulus in 1997. A short test sample with an 18-inch free length between the splices was used, and as weights were applied to one end with the other secured to the ceiling of the lab, the length (elongation) changes of the free length were measured as a function of applied weight (tension). Successively heavier weights were hung from the elastic tether in a high bay area until the weights reached the ground. After a weight was applied, about 10 minutes was allowed for the tether to reach equilibrium and the measurement taken. On the relaxation part of the curve, about 20 minutes was allowed between measurements after the removal of a weight. These results are compared with test results from T-1 through T-6 in Figure 35. At about 100% stretch on the ascending curve, the results agree well with T-2 data. The main difference is that the range of the static test stretch varied from near zero to over 200% and back to zero in one cycle, and the tether was not cycled around mean stretch. This is the case where it is moored with a given initial stretch, and then cycled about this by the waves and current fluctuations. That the results do tend to agree at this point, show that three tethers made a different times from different batches of rubber and new and used, and in different tests do agree in behavior, so that one should not expect the behavior to change drastically with time. The static test modulus does not increase as rapidly as the average modulus from the dynamic tests for the increasing elongation portion of the test. However, during the relaxation, the curve follows closely the results from T-5, indicating a similar behavior. The relaxation curve for the static test then falls below the dynamic curve smaller elongations.

4.9. Tabular Summary: The following tables summarize the determination of the elastic modulus from the load–elongation test results and use the same data used in the plots shown above. The following tables list the calculated elastic modulus as linear approximation from the load versus interpolated elongation curves of the test samples. The high stretch up to 260 percent shows the large compliance of the rubber tethers that allows the accommodation of wave heave and surge of a surface buoy in shallow water taut buoy moorings. The test results confirm the truly remarkable and unique property of rubber to stretch to and retract from high elongation under cyclic loading with only small changes in sample lengths. The at sea behavior of the rubber moorings prove that the tethers can stretch and retract around ½ million wave cycles per month for a year or more without showing signs of axial stretch fatigue.

Table 4: Data From Buoy Technology, Inc. 1997 Static Test.

Time (EST)	Weight (lbs)	Tether Length (inches)	% Elongation	Eye-Eye Length (inches)
0945	51	9.31	52	78.0
0955	74	11.38	86	87.0
1009	97	12.95	111	96.0
1020	119	14.38	135	103.5
1035	141	15.74	157	112.5
1050	163	16.88	175	121
1105	185	18.00	194	130.0
1120	208	19.00	210	138.0
1205	185	19.13	212	138.5
1225	163	18.88	208	135.0
1240	141	18.56	203	132
1255	119	18.06	195	127.25
1310	97	17.38	184	121
1325	74	16.38	151	110.5
1330	51	11.68	91	94.75

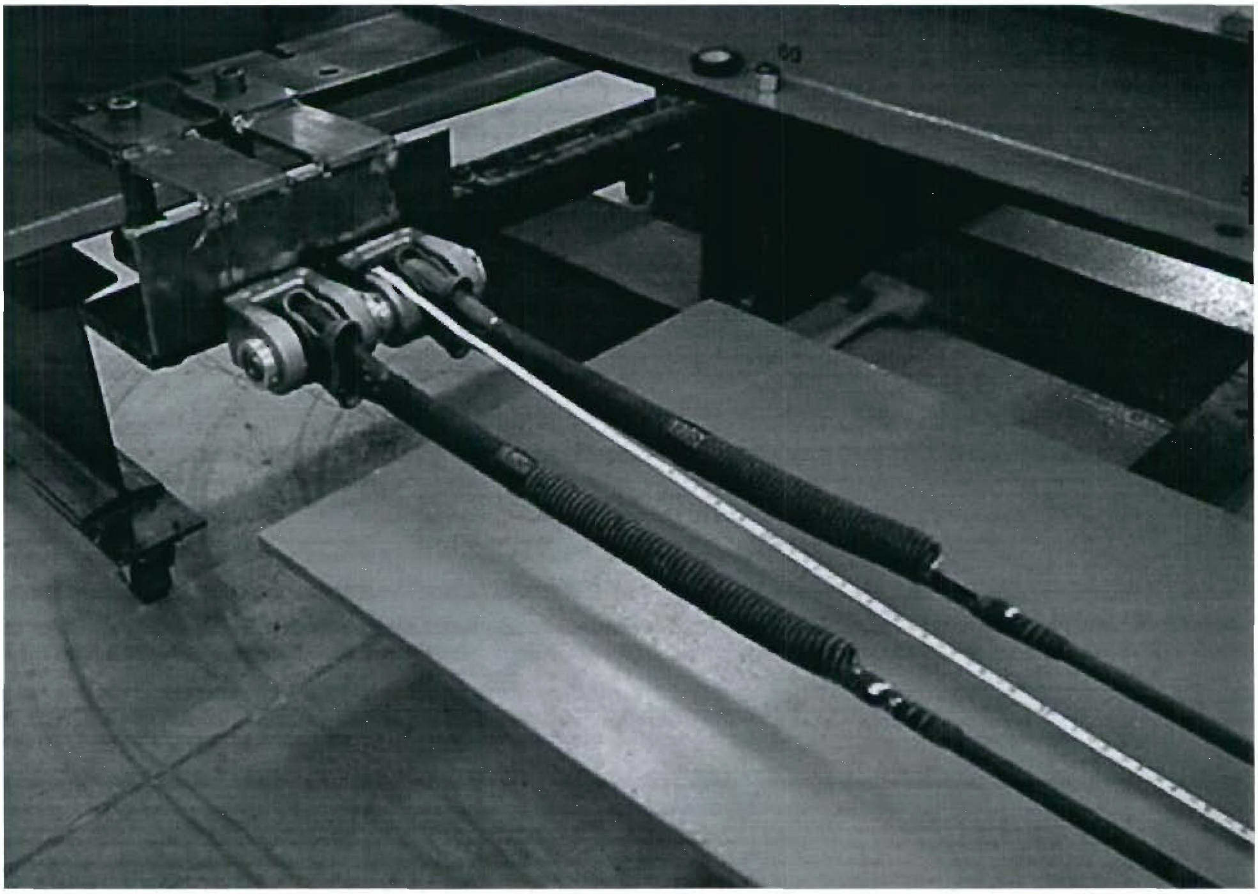

Figure 32. After the extended test, the tethers at the load cell end show slipping in the splices, which is shown in more detail in Figure33.

Figure 33. Detail of the splice slip in the tethers after the 3000 cycle extended test.

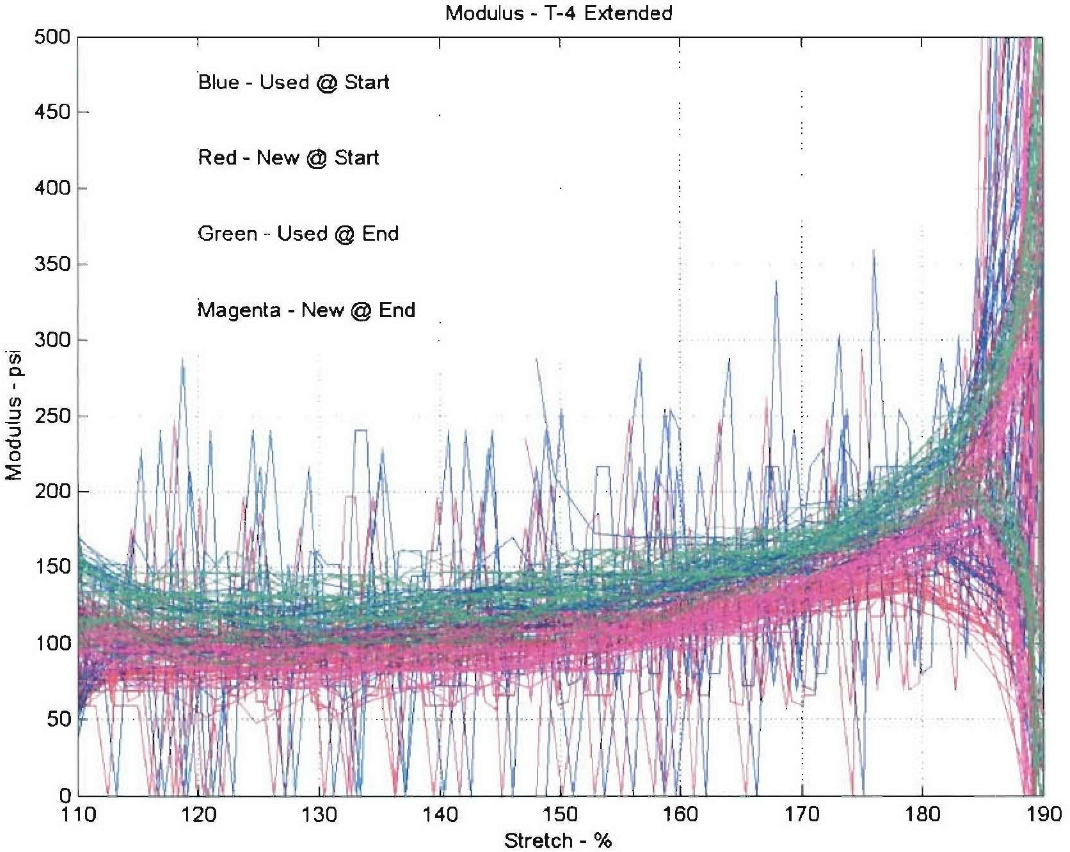

Figure 34. Elastic Modulus Versus Stretch, – for T4, Extended Fatigue start and end comparison for used and new elastic tethers. Data appears noisy because of the resolution of the recording, and the maximum and minimum elongation values where the rate of elongation was not constant were not removed as in previous plots.

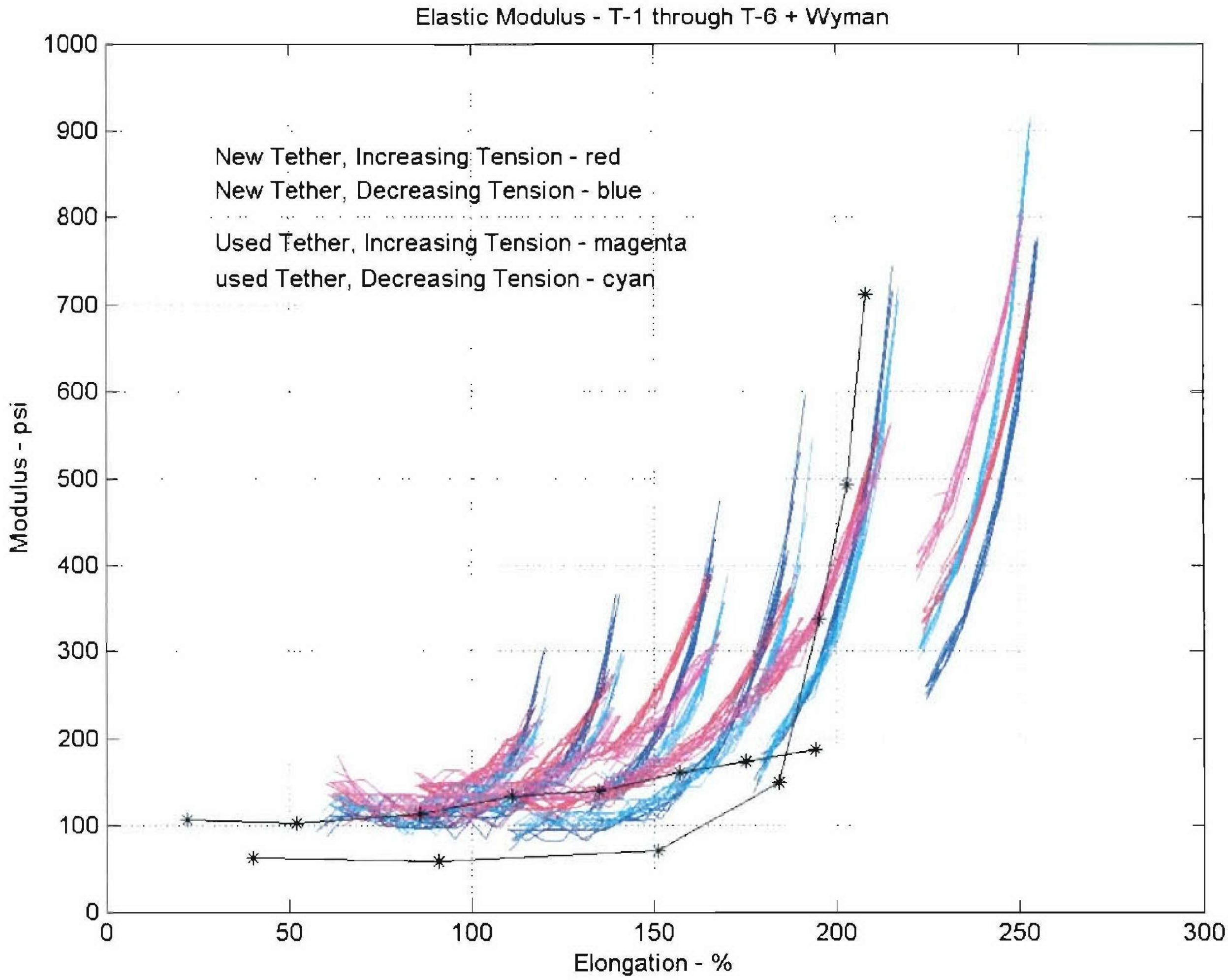

Figure 35. Elastic Modulus Versus Stretch, – for T-2, T-4 and T-5 from cycle around a mean stretch (Table 2) and Buoy Tech. Inc. 1997 static test.

6.0. Conclusions/Summary:

The modulus data presented must be considered approximate due to the visco-elastic nature of the rubber material used in the tethers. When the test machine has stretched the rubber tether to coincide with a selected extension and then stops, the tension will drop rapidly at first and then more slowly until it stabilizes. Therefore, the exact modulus obtained is somewhat time dependent. Which elongation (load) is selected is operator dependent, and so is the elastic modulus calculated. Waiting for long duration is not satisfactory because that is not the case in a mooring. At low tensions, the relaxation of the rubber was not noticeable, but it is at higher tensions. However, waves and currents don't wait for the rubber to reach full relaxation, so these tests are somewhat more realistic to practical operating modulus than a static test.

The new and used tethers tested very similar, with a tendency at higher elongations for the new tether to have higher moduli. However, the differences are not that large in the envelope of maximum and minimum envelope of modulus versus stretch shown in Figure 31. It is clear that using a single modulus is an oversimplifying, especially at higher elongations. The modulus

becomes more non-linear, and has a greater steepness of slope with elongation. Picking a modulus in the 110 to 150 range for smaller cycles around 100% elongations appears to be reasonable. However, the maximum tensions will be underestimated, especially at higher elongations where it is critical. With 25% cycling around 250% mean stretch, the maximum descending modulus of 900 psi is reached, which is 6 times that suggested for lower elongations. During relaxation on the low elongation part of a cycle, the modulus can drop below 100 psi. Therefore, these dynamic tests indicate a range of moduli for the elastic tethers that varies by an order of magnitude.

Table 5: Ascending Elastic Modulus values for new and used rubber tether tests T-1 through T-6 from Appendix B. Graphical data of the TMT Test Report

Test	Load, max [lbs]	Load min. [lbs]	Strain max.	Strain min.	Elastic Modulus [psi]
T-1 new	112	80	1.05	.275	137
	145	112	1.23	1.05	216
T-1 used	115	66	1.25	0.55	148
T-2 new	113	64	1.10	0.60	115
	130	113	1.23	1.10	154
	173	130	1.43	1.23	253
T-2 used	95	50	1.10	0.60	130
	140	95	1.45	1.1	185
T-3 new	133	113	1.45	1.27	196
	160	133	1.575	1.45	254
	207	160	1,725	1.575	369
T-3 used	123	90	1.55	1.285	179
	162	123	1.74	1.55	296
T-4 new	145	85	1.60	1.07	133
	231	145	1.95	1.60	289
T-4 used	123	70	1.60	1.07	144
	190	123	1.96	1.60	268
T-5 new	190	125	1.98	1.725	300
	278	190	2.18	1.98	517
T-5 used	164	113	1.98	1.75	319
	236	164	2.20	1.98	471
T-6 new	240	143	2.43	2.15	407
	322	240	2.58	2.43	643
T-6 used	2.40	143	2.43	2.15	499
	322	240	2.58	2.43	787
T-4 new after 3000 cycles	122	72	1.60	1.03	103
	159	122	1.90	1.60	145
T-4 used after 3000 cycles	113	68	1.60	1.05	118
	153	113	1.92	1.60	180

Table 6: Ascending Elastic Modulus values for new and used rubber tether tests T-1 through T-6 from Appendix C. Consolidated data of the TMT Test Report

Test	Load, max [lbs]	Load min. [lbs]	Strain max.	Strain min.	Elastic Modulus [psi]
T-1 new	145	80	1.22	0.80	191
T-2 new	127	62	1.20	0.60	128
	176	127	1.43	1.20	251
T-3 new	204	100	1.72	1.27	272
T-4 new	144	80	1.58	1.04	139
	230	144	1.93	1.58	289
T-5 new	275	124	2.19	1.72	378
T-6 new	340	145	2.62	2.17	510
T-1 used	118	63	1.22	0.78	180
T-2 used	98	50	1.10	0.60	138
	139	98	1.43	1.10	178
T-3 used	160	88	1.72	1.27	230
T-4 used	120	70	1.53	1.05	150
	190	120	1.93	1.53	252
T-5 used	170	112	1.98	1.72	321
	237	170	2.18	1.98	482
T-6 used	230	135	2.43	2.12	441
	320	230-	2.60	2.43	762

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16. Abstract (Limit: 200 words)

Compliance must be supplied to any surface mooring to allow the buoy to move with the waves and currents, and remain moored in position. This can be supplied with a traditional chain catenary or newer compliant elastic tether or stretch hose technologies. Some applications of each of these three techniques are shown, with the emphasis placed on the use of compliant elastic tethers. For modeling and designing these moorings, the elastic modulus of the tether material must be known. Therefore, a new and used piece of elastic material was terminated, tested for the stretch-strain relationship under set conditions, and the elastic modulus calculated. For these tests, the elastic tether was stretched out to a mean elongation between 100 and 250%, then cycled about that stretch by ±25 and ±50% to duplicate a moored application. The resultant elastic modulus is presented to aid in mooring design. At low elongations, the elastic modulus is constant at about 125 PSI, but as the mean elongation increases the modulus increases, and as the cycle tension increase the modulus also increases, reaching a maximum of 900 PSI at 275% stretch.

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